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A SEISMIC REFLECTION CRUSTAL MODEL NEAR EDMONTON, ALBERTA

by

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The undersigned certify that they have read, and recommend to the Faculty of Graduate Studies and Research, for acceptance, a thesis entitled A SEISMIC REFLECTION CRUSTAL MODEL NEAR EDMONTCN, ALBERTA submitted by David Charles Ganley in partial fulfilment of the requirements for the degree of Master of Science.

ABSTRACT

Seismic reflection data recorded close to the geophysical observatory at Edmonton, Alberta have been interpreted to produce a crustal model for this area. Velocity analysis was performed with the aid of a computer program, written specifically for this work, which does not require common depth point data and which will allow for substantial dip on reflecting interfaces. The model shows the presence of 15 degree southeasterly dips within the crust, with the base of the crust essentially flat. Total crustal thickness of 35.5 kilometers is indicated.

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CHAPTER 1

INTRODUCTION

1.1 History of Crustal Studies

The earth's crust or outer shell has always been of greater interest to seismologists than its small size would suggest. There are several reasons for this. Since this region completely encloses the rest of the earth it will affect any measurements made on deeper regions. Without a good knowledge of crustal structure it would be difficult to obtain precise information about the interior of the earth. The second reason for the interest in the crust is the effect it has on man. The crust is the source of the earth's ores and minerals and a knowledge of the relationship of crustal properties to location and formation of these reserves is valuable both economically and to our well-being. Another important consideration is the earthquake prediction problem. If we hope to predict earthquakes then a detailed knowledge of the crust and upper mantle may be important.

The first studies of crustal structure were made through observations of near earthquakes. The initial discovery occurred in 1910 when Mohorovicic identified the velocity discontinuity which now bears his name. This is referred to as the M discontinuity and is generally accepted

as the base of the crust. In 1925 Conrad reported a discontinuity above the M which does not seem to be as universal as the M discontinuity. The Conrad discontinuity is generally regarded as the transition between a granitic crust above and an intermediate layer of more basic composition below.

Explosion seismology has proven to be the most powerful tool for studying crustal structure. This method was first applied in petroleum exploration in 1921 by Drs. J. Clarence Karcher, William P. Haseman, Irving Perrine and Mr. William C. Kite (Schriever, 1952). None of these people could have predicted at that time the success this method would have. It is today the most widely used and effective of all petroleum prospecting methods (Allen, 1971). These techniques have been applied to studies of the deep crust and both refraction, and more recently reflection, methods have been employed.

The first published report of deep crustal reflections was made by Junger (1951). During normal seismic work in Big Horn County, Montana the recording camera was allowed to run for 10 seconds to study a long-lasting, low-frequency surface disturbance set up by a 25 pound charge. The resulting record showed a reflection at 8.5 seconds. Other records were obtained in adjoining areas which showed reflections at times of 7.0 to 7.5 seconds. The recording of these reflections was found to be repeatable, and on the

basis of the energy they contained, Junger argued that they could not be multiples and must be reflections from inside the basement. Other isolated instances of deep reflections were reported and a good summary of these reports and the arguments for and against the existence of such reflections can be found in Steinhart and Meyer (1961).

A later review by James and Steinhart (1966) describes the results of reflection and refraction crustal studies from 1960 to 1965. An excellent recent review of seismic crustal studies in all parts of the world can be found in Chapter 3 of the Geophysical Monograph 13 (Hart, 1969). This work contains a collection of papers by different authors pertaining to studies in many countries. A brief summary of this work follows.

Seismic explosion studies in western Europe have been made by reflection and refraction surveys of petroleum companies, quarry explosions of mining companies and scientific explosions in the sea, Alpine lakes and in boreholes (Closs, 1969).

In the Alpine region, refraction work has been done mainly by workers in France, Germany, Italy and Switzerland. They found a general thickening of the intermediate layer along the southern inner margin of the Alps. A great deal of work was done in central France, also. Shots in the North Sea and the Irish Sea have led to a crustal model with a very thin, or non-existent intermediate layer.

In northern Europe surveys have been carried out in Finland, Sweden, Norway and Denmark. Good review articles for each of these countries can be found in a publication edited by Vogel (1971). Velocities and thicknesses of granitic and basaltic layers as well as mantle velocities are given for Finland, Sweden and for three profiles in Norway. A refraction study in Denmark has suggested a very thin granitic layer in that area.

In Germany a great deal of crustal structure work, much of which is based on reflection seismology, has been done. Most of the German work is statistical in nature, involving histograms which show the number of reflections in a certain area as a function of reflection time. A comprehensive review of the German work on deep crustal reflections is given by Dohr and Fuchs (1967). They found that deep reflections only correlate over short distances and exhibit considerable scatter in reflection times. A short review article which presents a diagram of the deep crustal structure of Germany and provides an extensive list of references of German work is given by Stein (1971).

An analysis of wide-angle reflections in Germany and the USSR led Meisner (1967) to suggest that the M discontinuity is stepwise, interrupted by rhythmically arranged series of partial melts of lower velocity. Fuchs (1969) demonstrated that a simple layered model of the reflecting horizons in the earth's crust was not consistent

with certain observations, especially the large amplitudes and low cut-off frequency of deep reflections. He suggested a laminated transition zone with a series of velocity reversals as a model for deep crustal reflectors.

Crustal studies in southeastern Europe have been carried out by several countries and are reviewed by Sollogub (1969). Most results come from refraction profiles, although good reflections from the M discontinuity were observed in Hungary. The earth's crust in the Carpatho-Balkan area was found to be a layered structure with seismic interfaces in addition to the M and Conrad discontinuities. The existence of mountain roots under the Crimean structures, Carpathians and Dinarides was proven and evidence of "anti-roots" along the Conrad discontinuity was found. Thicknesses and velocities of individual layers were mapped throughout these countries.

In Russia results have been obtained with the deep seismic sounding (DSS) method designed by G. A. Gamburtsev in 1948 to 1955 and commenced in 1956 (Kosminkaya et al, 1969). A description of the Soviet techniques and observational methods along with information about use of reflected and refracted waves can be found in Kosminkaya and Riznechenko (1964). This review also gives cross-sections and a discussion of the nature of stratification. Another excellent review which describes almost all aspects of the DSS program up to 1962 is given in a collection of Soviet

papers edited by Zverov (1967).

Kosminkaya et al (1969) present crustal models of 17 different tectonic zones within the USSR. These models give layer thicknesses and boundary velocities of the major crustal layers. They are all characterized by block structure, different depths to the M discontinuity, different layer thicknesses, different layer velocities and an M boundary velocity of 8.0 to 8.2 km/sec.

The Vela Uniform program and the Upper Mantle Project provided a strcng impetus to explosion seismology in North America. Refraction studies to determine crustal thickness and layer velocities were made on about fifty profiles. Many of these results are reviewed Healy and Warren (1969). The upper crustal layer was found to have a P-wave velocity range of 5.9 to 6.2 km/sec and the lower layer a range of 6.6 to 7.1 km/sec. In some areas a second deep crustal layer was found with a velocity of 7.1 to 7.4 km/sec. The P-wave velocity of the uppermost mantle ranges from 7.8 to 8.3 km/sec with the lower velocities predominant in southwestern United States.

Although much refraction work was done in North America prior to 1969, very few reflection studies were made. In fact, prior to 1968 the only North American group to use the reflection technique for studying crustal structure was at the University of Alberta (Clowes, 1969). This work will be reviewed later as it forms a prelude to this thesis.

Studies of crustal structure of the Atlantic Ocean began shortly after World War II (Ewing, 1969). By 1960 over one hundred refraction profiles had been recorded. One of the most significant results was the discovery that the crust is much thinner under the oceans than under the continents. The typical crustal structure consists of a sedimentary zone at the top with a P-velocity of 1.3 to 3 km/sec, a second layer of velocity 4.5 to 5.5 km/sec and a lower layer of velocity 6.5 to 7.0 km/sec. Mantle P-wave velocity ranges from 7.4 to 8.4 km/sec beneath the ocean. The M discontinuity has an average depth under the Atlantic of 12 km and apparently disappears under the mid-Atlantic ridge. Similar structural features were found under the Pacific and Indian Oceans (Shor and Raitt, 1969).

Japan too, has been active in seismological studies of the crust. A model of crustal structure for a cross-section of north-eastern Honshu has been prepared (Research Group for Explosion Seismology, 1968).

1.2 Crustal Studies at the University of Alberta

The first seismological determination of crustal thickness in Alberta was that of Richards and Walker (1959). A team of fifteen seismic parties made measurements along an 81 mile refraction profile. This profile was parallel to and about sixty miles east of the frontal thrust of the Rocky Mountains. They obtained a depth of 43 km to the M

discontinuity and an upper mantle velocity of 8.2 km/sec. In addition they identified the Conrad discontinuity dipping at about 3 degrees to the south at a depth of 29 kilometers and with a velocity of 7.2 km/sec. Some evidence was found for other additional layers.

The first use of explosion seismology at the University of Alberta for the study of crustal structure was made by Cumming, Garland and Vozoff (1962). Several shots were made at each end of an east-west refraction profile 250 kilometers long in southern Alberta. They arrived at a preferred model which consisted of three layers between the top of the Precambrian and the Mantle. The uppermost layer was a Precambrian basement basic phase with a mean thickness of 20 km and a velocity of 6.4 km/sec. A velocity reversal was postulated and the thickness of a layer with velocity of 6.1 km/sec was 11 km. A deep crustal layer with a velocity of 7.32 km/sec overlay the mantle which had a mean depth of 47.5 km and velocity of 8.25 km/sec. In all cases dip was less than one degree.

Cumming and Kanasewich (1966) reported the results of an extension of the previous work along two reversed refraction profiles extending east and west from Suffield, Alberta for a total distance of 500 km. In addition, a one-way refraction profile extending west into the Rockies was shot. The revised crustal model which they arrived at from these studies consisted of three layers between the basement

and upper mantle. The uppermost layer referred to as the basement layer was found to have a velocity of 6.1 km/sec. Thickness of this layer ranged from 15 kilometers in some areas to zero just west of Suffield. The disappearance of this layer correlated with a steep gradient in the Bouguer gravity anomaly along the seismic line. The second layer, referred to as the sub-basement, extended to depths in the range of 33 to 37 km and had a velocity of 6.5 km/sec. Below this, the third or intermediate layer had a velocity of 7.15 to 7.2 km/sec and was underlain by the upper mantle with a velocity of 8.1 to 8.3 km/sec. The total crustal thickness ranged from 43 to 49 km.

The first observation of deep reflections in Alberta was made by Robertson (1963) . During the course of routine seismic reflection work in southwestern Alberta deep reflections at times of three to five seconds were observed. These were shown to be reflections from within the Precambrian basement and not multiples. The reflecting layers had a dip of eight degrees or more.

The first deep reflection work at the University of Alberta was a study of near-vertical-incidence seismic reflections at Lomond, Alberta by Kanasewich and Cumming (1965). They recorded good quality reflections at a time of 11.4 seconds along an expanding spread. The use of horizontal geophones showed that the event was near-normal incidence. An x-squared, t-squared analysis gave an average

velocity from the top of the Mississippian to this reflector of 6.37 km/sec and a depth to the reflector of 34 km. This was in good agreement with the depth to the discontinuity observed in the refraction profile reported by Cumming et al (1962). However, since the velocities were different than for the Conrad in Europe and in order to avoid implying intercontinental correlation, this discontinuity has been referred to locally as the Riel or R discontinuity as suggested by Professor D. H. Hall of the University of Manitoba.

As a result of the success of the preceding work, the deep crustal reflection program at the University of Alberta was expanded. The results of these studies were first reported by Clowes, Kanasewich and Cumming (1968). Seismic reflections over four profiles for a total of about 90 kilometers in southern Alberta were studied. Power spectral calculations showed that the energy of the reflected wavelets was concentrated in the five to fifteen Hertz range. Along one profile the reflection from the R discontinuity was correlated over nearly 25 kilometers. Analysis of this data gave a revised average vertical velocity of 6.2 km/sec to a depth of 34 km. Other reflections were recorded from layers near the base of the crust including a layer corresponding in depth with the M discontinuity as determined by refraction studies. Continuous profiling along a 40 km line allowed construction of a seismic cross section which was characterized by 8 km

of relief over a horizontal distance of 25 km. This pointed out how the reflection method could be used to map complicated structure involving steep dips within the deep crust.

These deep structures have been interpreted as a Precambrian rift valley lying below the flat sediments (Kanasewich, 1968). Seismic velocity data combined with measured Bouguer gravity anomalies led to a crustal model indicating that this rift valley was filled with lower density material. This rift was traced by gravity and magnetic trends for several hundred kilometers across Alberta and into British Columbia (Kanasewich et al, 1969).

All of these previous studies had been concerned with obtaining crustal models of velocity-depth structure. In 1970 Clowes and Kanasewich studied the attenuation properties of the crust and the nature of the reflecting horizons (Clowes and Kanasewich, 1970). Using a synthetic seismogram program which included attenuation as function of frequency and depth, they attempted to obtain a model of the Q structure of the crust. They suggested that Q varies considerably above the basement with an average of about 300, and that below the basement Q is approximately 1500 and probably increases with depth. In addition to Q studies they used spectral analysis to examine the nature of the transition zones. They concluded that first-order discontinuities, linear gradients and step-like velocity

increases gave generally unfavourable spectral characteristics. They found that a transition zone model consisting of sills of alternating high and low velocity material was in agreement with the observed data. The layers in this model were less than .2 kilometers thick and extended over a zone less than 1 kilometer in thickness.

Chandra and Cumming (1972) continued the interpretation of refraction data in the area. They reported the interpretation of a 760 km refraction profile from Greenbush Lake, British Columbia to Swift Current, Saskatchewan with all the older refraction work included. They examined this seismic refraction data in conjunction with reflection results and gravity and magnetic surveys in order to arrive at a unified interpretation for the area. Upper crustal velocities vary laterally from 6.1 to 6.5 km/sec and boundaries between the velocity zones are most probably near vertical faults involving the whole crustal section through to the M discontinuity. The areas of 6.5 km/sec upper crustal velocity are in regions where the 6.1 km/sec layer is absent. The velocity beneath the two layers is 7.15 to 7.17 km/sec and the upper mantle velocity varies from 8.0 km/sec west of the Rockies to 8.3 km/sec in a region between Vulcan and Suffield where the profile crosses the Sweetgrass Arch.

In addition to the explosion seismic studies of the crust in Alberta some attempt has been made to determine

crustal structure by studying the P-coda on earthquake seismograms. Ellis and Basham (1968) compared vertical to radial spectral ratios with theoretical ratios calculated using the Thomson-Haskell matrix formulation. They noted large deviations between experimental and theoretical curves, particularly at the University of Alberta Edmonton seismological observatory, and they attributed these deviations to shear wave conversion and scattering in the crust. They also found that for 20 events the observed azimuth was approximately 18 degrees more northerly than the true azimuth. This could be explained by localized dips of approximately 15 degrees on the crustal boundaries.

In a more recent paper Somerville and Ellis (1972) suggest a crustal model for the same area which gives better agreement with experimental P-coda studies. This model was obtained by studying vertical to radial spectral ratios with the aid of synthetic seismograms. They found that a reasonable comparison between theoretical and experimental results could be obtained by including a low velocity layer several kilometers thick at a depth of 12 kilometers.

Another application of the P-coda spectral ratio method to the problem of determining crustal structure was made in the same area by Sprenke (1972). He could find no exact match between a theoretical and an observed spectral ratio but he did suggest the possibility that the upper crust is typified by 1) a very low S-wave velocity in surficial

layers, 2) a Poisson's ratio of one-third in the softer sedimentary layers and 3) a low velocity layer approximately 3.5 km thick in the basement immediately beneath the sediments.

CHAPTER 2

THE PROJECT

2.1 Introduction

As a result of the success with deep crustal reflections in southern Alberta, it was decided that work should be done near the seismic observatory at Edmonton. The interpretation of P-coda studies would be facilitated by a detailed model of the crust in this area. An additional consideration was the availability of well velocity surveys. Figure 2.1 shows the location of the site chosen and nearby wells for which velocity information was available.

Figure 2.2 shows the actual layout of the profiles for the shots. The recording set-up consisted of twelve groups of geophones spaced with 880 feet between centres. This, along with the 440 feet of spacing at each end, gave a total layout of two miles. Each receiver group consisted of sixteen geophones laid out in a tapered array, the advantages of which are described by Clowes (1969).

Three spreads were used for the collection of data in the summer of 1971. On August 25 the recording array was along the profile AB in figure 2.2 and a 40# and two 20# shots were fired at point A. The profile was along CD on September 2 and 40# shots were fired one, two and three miles from each end at points A, P2, P3, P4, P5 and P6.

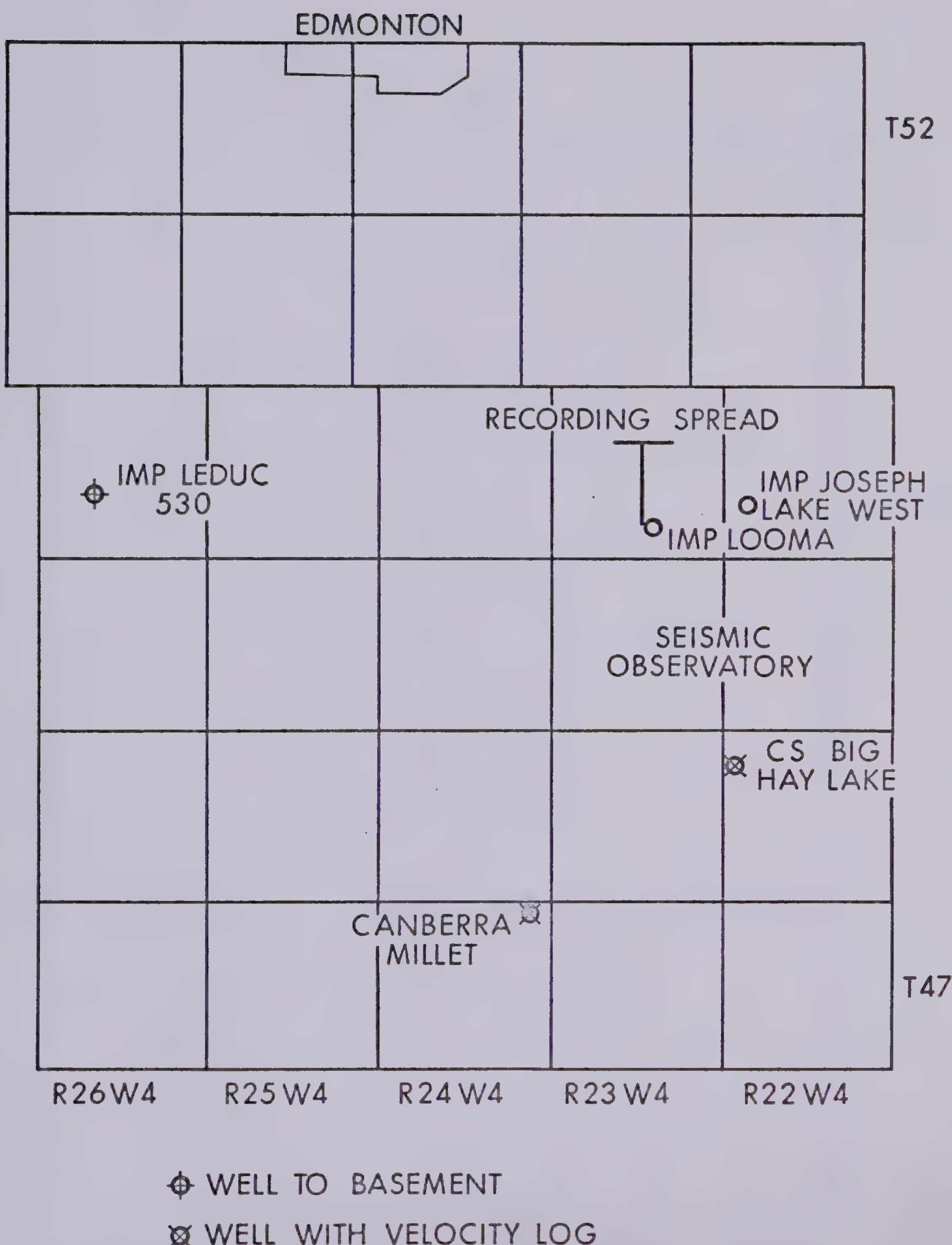


Figure 2.1 Project area map.

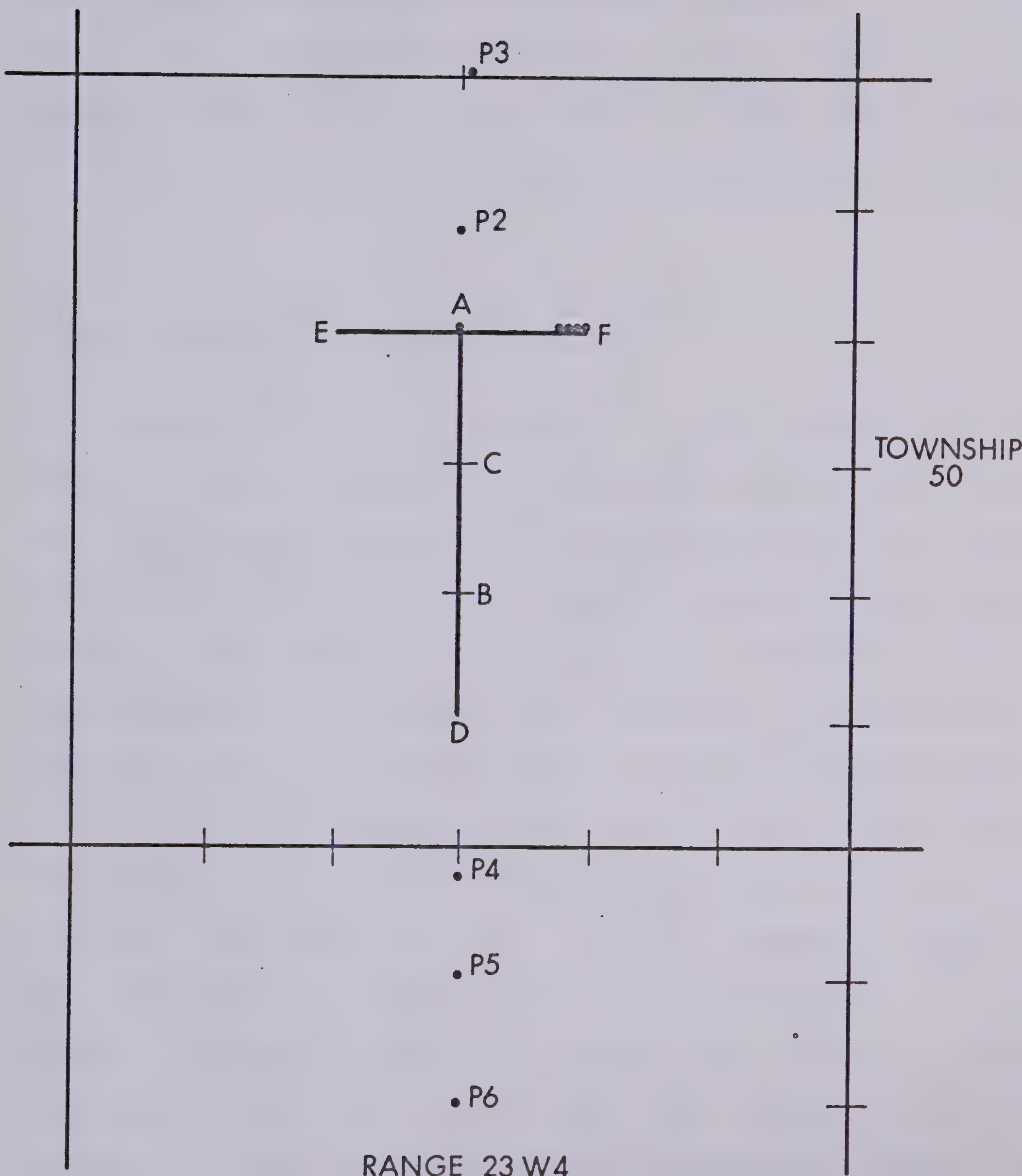


Figure 2.2 Layout of the profiles.

For the shots at A, P2, P4 and P5 a pattern of holes as discussed by Clowes (1969) was used. For the remote shots at P3 and P6 patterns were not deemed necessary. The third spread, EF, was used on September 23 for five shots in single holes. One 5# shot was at A and four 10# shots started at F with successive 440 foot displacements towards A.

2.2 The Digital Recording System

Figure 2.3 is a schematic of the circuit for each channel. The seismometer shown represents the output from the 16 geophone array of Electro-Tech EVS-4 7 1/2 Hertz seismic detectors. Each data channel consists of the output of one of these arrays. RL is the line resistance and is proportional to the distance from the array to the recording position which is in the center of the 12 channel spread. RX is a variable resistance such that RL + RX = 700 ohms. This value of resistance provides the optimum damping of the geophones in crder to give flattest frequency response. Thus, the output of each channel is proportional to the factor $R'/(R'+RL)$ where $1/R'=1/RX+1/10k$. Since RL varies with position of the array then each channel must be normalized by the appropriate factor $(1+RL/RX+RL/10k)$ before amplitudes can be compared.

In addition to the twelve data channels two other channels were recorded, one for the shot instant from a

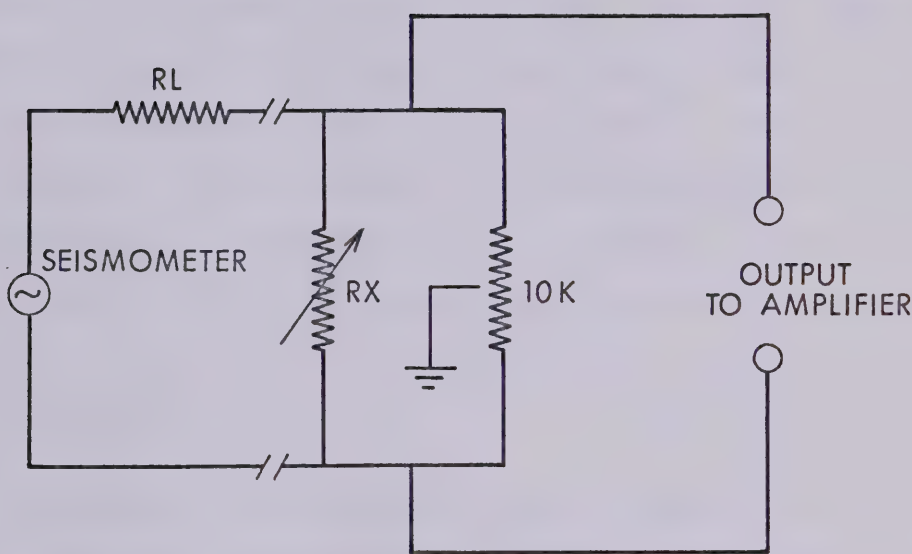


Figure 2.3 Schematic of seismometer line resistance.

radio receiver and the other for absolute time from WWVB. These fourteen channels were recorded digitally on a 9-track synchronous tape transport with a tape velocity of 6.25 inches per second. The recording density is 800 bpi and hence the data transfer rate is 5000 bytes per second.

The signal is converted from analog to digital form by a converter with a resolution of 13 bits plus sign, providing a dynamic range of 84 db. Two 8-bit bytes are required to store each sample of the input signal and hence the sampling rate is 2500 times per second. Since there are 14 channels, each channel is sampled once every 14/2500 (.0056) seconds. This results in a Nyquist frequency of 89.29 Hertz. One of the two unused bits in each two byte sample is used to mark the end of one data conversion frame for all channels.

In writing the records onto tape a length of 8192 bytes (4096 samples) per channel was chosen. This yields a time interval of 22.94 seconds. Since fourteen channels were being recorded the block length on tape is 114,688 bytes. The inter-record gap results in the loss of .096 seconds of data when more than one block is written.

Figure 2.4 is a diagram of the complete system. The tape recorder is a Model 7830-9 write-only transport made by Peripheral Equipment Corporation. The multiplexer, analog to digital converter and 5 kHz crystal clock plus associated interfaces and controls are contained in a modified Model

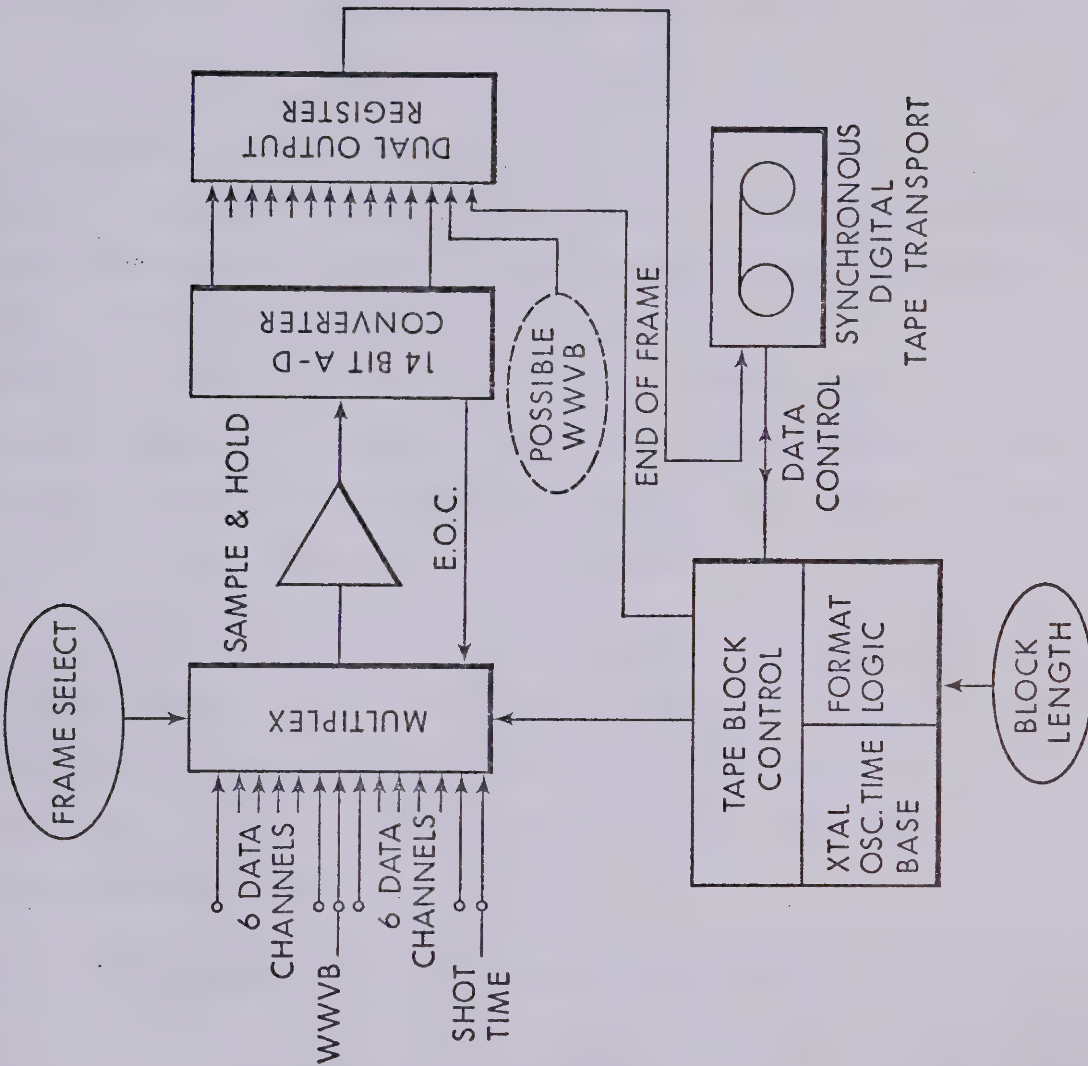


Figure 2.4 Block diagram of recording system.

#120 Data Acquisition System which was manufactured by Datum Inc. Controls allow the selection of from one to twenty channels for recording purposes and allow the choice of record length up to the maximum of 4096 samples per channel.

Figure 2.5 shows the amplifier circuit. An input transformer of 18 db gain drives a 40 db fixed gain pre-amplifier which feeds the main amplifier through a high-pass two pole Bessel filter. A Bessel filter was used because of its linear phase shift properties. The latter may be by-passed. The main amplifier has switchable gain and its output passes through a four pole Bessel aliasing filter with a 50 Hz corner. Figure 2.6 shows the amplifier gain when the high-pass filter is by-passed.

Figure 2.7 illustrates the type of data obtainable with this system. The upper half of the figure is part of the photographic monitor record of a 40 lb shot recorded at 88 db gain setting. The lower traces are a Cal-Comp plot of the digitized data.

This system has been described by Allsopp et al (1972).

2.3 Velocity Log above the Basement

In order to obtain reasonable values for the velocity in the lower crust it is essential to have reliable information about the velocity distribution in the overlying rocks. Therefore continuous velocity logs were obtained for

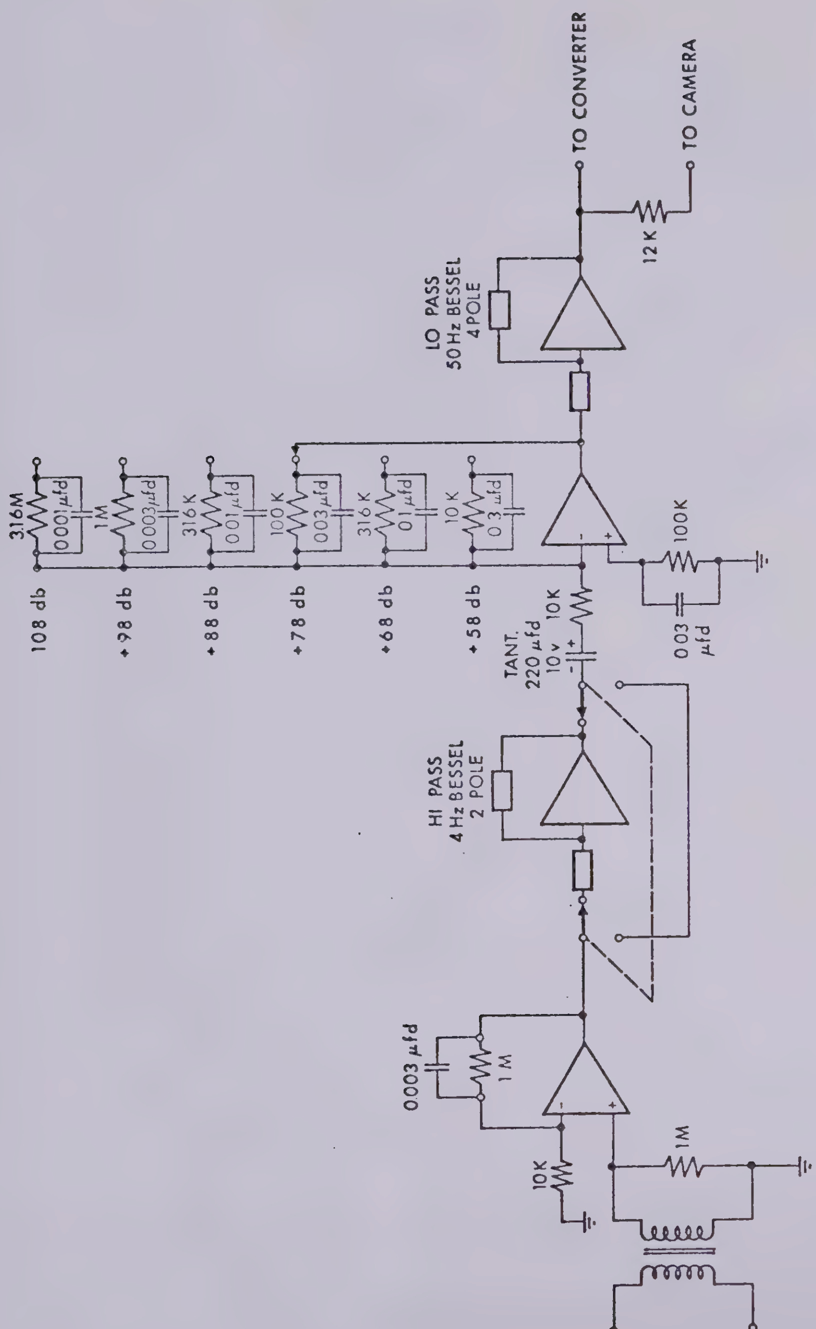


Figure 2.5 Amplifier circuit.

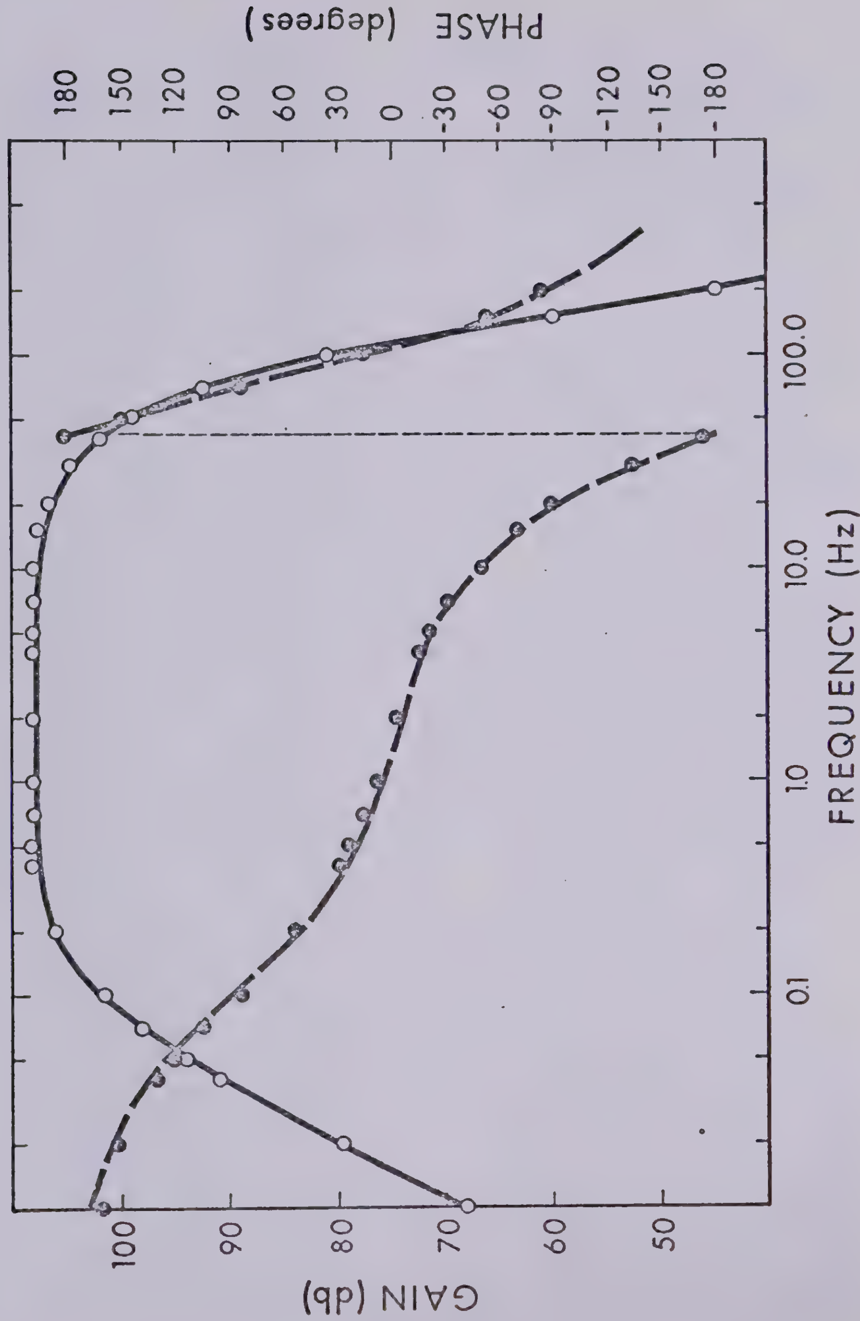


Figure 2.6 Amplifier response. Curves are calculated from circuit parameters and circles are measured points.

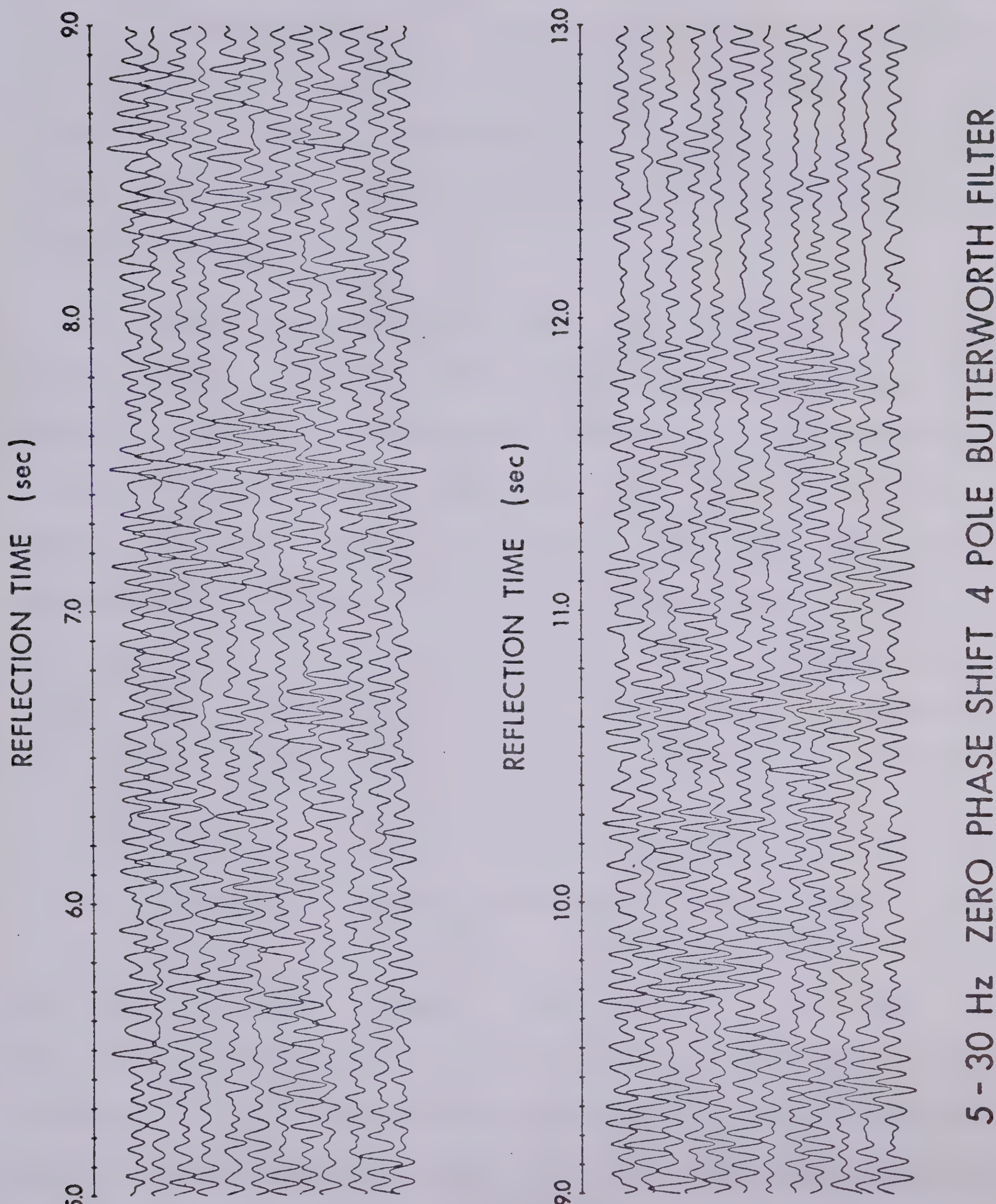


Figure 2.7 Comparison of photographic and digital records.

the Big Hay Lake and the Canberra Millet wells shown in figure 2.1. The original logs gave average travel times for ten foot intervals, but no total travel times to formations. These were simplified by combining all regions where interval velocities in successive 10 foot layers were within 3 per cent of each other into one thicker layer, with travel time being conserved.

Depths to formation tops were also available for all wells shown in figure 2.1. These showed the sedimentary layers in this area to be essentially flat. Close agreement exists in depths for the Big Hay Lake and Looma wells. Since the Looma well was near to the reflection profile, it was decided to adjust the velocity log for Big Hay Lake to fit this well. Both times and depths were available for the Looma well. This adjusted log would be used as a velocity model for the sedimentary rocks in the area of the profile.

In order to match the formation depths in the two wells it was necessary to correct for the 150 feet greater depth to the top of the limestone in the Big Hay Lake well. Electric logs were obtained for the two wells and, by comparison of these logs, it was possible to ascertain which sections of the upper sediments should be removed from the velocity log in order to make the Big Hay Lake velocity survey compatible with the Looma well. In addition to this it was necessary to change the Wabamun velocity from 18,300 to 19,200 ft/sec in order to match travel times in the

Paleozoic section.

Since the velocity log began at a depth of 570 feet, a velocity model based on the hammer seismic results reported for this area by Sprenke (1972) was chosen for the top of the log. Also, the continuous velocity log did not extend to the basement, and so it was necessary to construct a velocity model from the travel times given for the bottom section of the Leduc #530 well which was drilled to the basement. The location of this well is shown in figure 2.1. Table 2.1 compares elevations relative to sea level and one-way travel times for the Looma well and the adjusted velocity log, and shows the good agreement which was obtained.

A sample seismic record from near this area was obtained from Imperial Oil. This was compared to a synthetic seismogram calculated using the adjusted velocity log. The comparison was quite good although we did not know the effect of automatic gain control or the nature of the filtering done on the Imperial record. It is felt that this procedure yields a good approximation to the velocity distribution in the sediments and will provide an adequate model on which to base further analysis of deep reflection data.

TABLE 2.1

FORMATION	ELEVATIONS (FT)		TRAVEL TIME (SEC)	
	Looma	New Log	Looma	New Log
Lea Park	670	670	.200	.200
Second White Specks	-480	-480	.322	.321
Viking	-900	-900	.366	.364
Wabamun	-1730	-1720	.444	.443
Cooking Lake	-3060	-3050	.525	.525
Beaver Hill Lake	-3310	-3310	.537	.540
Elk Point	-4010	-4010	.576	.574

CHAPTER 3

COMPUTER PROGRAMS

3.1 Methods of Velocity Analysis

Determining seismic velocities by means of reflection profiles is a very old technique in the field of geophysics. One of the first reports of the method was given by Green (1938). He described the classic method of plotting recording distance squared against reflection time squared to give a straight line with slope equal to velocity squared. By using this method it is possible to obtain velocities within 3 per cent of the correct values (Gardner, 1947). A detailed discussion of this method was given by Dix (1955). All of these papers referred to common depth point shots. More recently, particularly during the last three or four years, the seismic exploration industry has given considerable attention to the development of computer velocity analysis systems (Montalbetti, 1971). A brief discussion of some of the principles involved in these methods will be given.

In all of these methods it is assumed that the common depth point method has been used in recording the data. This method was outlined by Mayne (1962). Additional discussions of this method were given by Mayne (1967) and Courtier and Mendenhall (1967). The method provides for

multiple coverage of the same subsurface points with different shot and detector positions. The effectiveness of this method is dependent on applying the proper time corrections to each trace so that the primary reflections will be moved in phase and properly stacked. One requires, as a result, a method to calculate corrections for all the traces with their different shot point to geophone distances.

For a simple horizontally layered model these time corrections could be computed from the equation

$$T(x,n)^2 = T(o,n)^2 + X^2/V(n)^2 \qquad (3.1)$$

T(x,n) is the two-way travel time at offset X for layer n

T(o,n) is the two-way normal incidence time for layer n

V(n) is the RMS velocity as given by Dix (1955)

$$V(n)^2 = SUM\{v(i)^2 t(i)\}/SUM\{t(i)\} \qquad (3.2)$$

SUM indicates summation over index i from 1 to n

v(i) is interval velocity of the i'th layer

t(i) is two-way normal incidence time in i'th layer

Now, the two-way normal incidence time for layer n is

$$T(o,n) = SUM\{t(i)\} \qquad (3.3)$$

and the interval velocity for layer n is

$$v(n)^2 = [V(n)^2 T(o,n) - V(n-1)^2 T(o,n-1)] / [T(o,n) - T(o,n-1)] \tag{3.4}$$

A derivation of equations 3.1 and 3.2 is given in Schneider and Backus (1968) and Taner and Koehler (1969). In the presence of dipping beds, model experiments have shown that the time-distance relations still remain nearly hyperbolic. However, the RMS velocity now obtained is only an apparent stacking velocity and should not be used to calculate interval velocities unless corrections are made for dip (Taner et al, 1970).

In general, the method of velocity determination from reflection data is done on a grid system. A value of T(o,n) is chosen and V(n) is varied between some minimum and maximum. Each value of T(o,n) and V(n) defines a particular set of time corrections. These corrections are applied to the data and a coherency measure is computed for each time correction. The final display shows this coherency measure plotted as a function of incidence time and RMS velocity. Peaks in the display indicate arrivals of coherent energy at particular values of incidence time and RMS velocity. Such a display is referred to as a velocity spectrum.

The coherency measure is computed within some time gate centred about the time corrections for each trace as

calculated by equation 3.1. It may take many forms from simple summing or normalized summing of traces to more complicated cross correlation techniques. Garotta and Michon (1967) use summing of traces as a coherency measure while Schneider and Backus (1968) describe a technique based on cross correlations. Taner and Koehler (1969) give two coherency measures. One is a sum of cross correlations between pairs of traces while the other is a function which they call the semblance function. A good review of various coherency measures is given by Montalbetti (1971).

Robinson (1969) describes a high resolution velocity technique which performs the calculation of a velocity spectrum in the frequency-wavenumber domain. In comparison to a cross correlation method in the space-time domain this method is faster on a computer.

3.2 The Velocity Program Used in this Thesis

If the common depth point method is not used for recording the data, the velocity spectral methods discussed in the preceding section are still applicable for uniform, flat layering. However, if significant dips are present on the interfaces, the velocity spectra can not be used for determination of interval velocities. In such a case it is necessary to find a different approach to velocity determination using the computer. Due to the severe restrictions imposed on shotpoint and detecter locations by

the extensive farming activity in the area it was not possible to arrange the profile to conform to the usual requirements of the common depth method. Further, a preliminary analysis of the data indicated that large dips were present on the reflecting horizons. Therefore a velocity program was written specifically for application to the particular set of data that was used in this thesis. This program was designed for determining velocities, depths and dips of layers within the basement and requires a known velocity model for the region above the basement. Models consisting of one or two layers within the basement may be treated although the program could easily be generalized to handle more layers. Straight-line ray paths within the layers have been assumed.

The program can be briefly summarized as follows. A particular velocity, normal incidence time and dip will specify one model of the crust. Knowing the shot to detector distance one can solve iteratively for the ray path corresponding to this distance for this particular model. This allows calculation of the travel time for each shot to detector distance. A time correction is applied to each trace on one record and a measurement made of the coherency of the energy arriving along this time correction. By systematically varying the velocity, incidence time and dip one calculates the coherency measure as a function of these three parameters and peaks in this display will indicate in-phase arrivals of energy.

The detailed operation of this program can be understood from examination of figure 3.1 which illustrates the case where there is only one layer below the basement. The ray path is ABCDE. The sections AB and DE represent the path through the layers above the basement. The parameters which are specified are the velocity in the first layer, V1, the dip of the boundary at the bottom of the layer, c1, and the normal incidence time for this layer, T1. The normal incidence time is the time it would take a P wave to travel from a point directly below the shot to the bottom of the layer and back along a path perpendicular to the bottom of the layer.

The program assumes that the top of the basement is flat which is consistent with the velocity model and formation depths frcm wells in the area as described in Chapter 2. Using the velocity model for the above-basement region and assuming straight line paths in the various layers of that model one can, with the aid of Snell's law, calculate travel time and x-distance travelled by a ray making an angle a1 with the normal just above the basement. Table 3.1 gives travel times and x-distances for various values of a1. For the purpose of the program, values for x-distance are stored in a table for integral values of a1 and interpolation is used to obtain an exact value when a1 is not an integer. Sufficient time accuracy for any angle between two integral values of a1 may be obtained by using

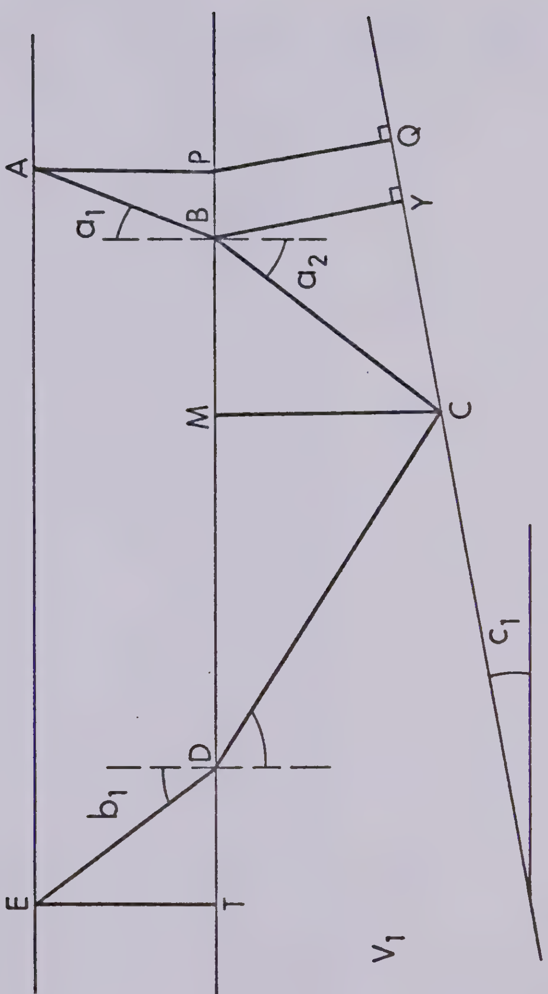


Figure 3.1 One layer model diagram.

TABLE 3.1

a1 (deg)	Travel Time (sec)	X-distance (meters)
0.0	0.724	0
1.0	0.724	36
2.0	0.724	72
3.0	0.725	108
4.0	0.725	144
5.0	0.726	180
6.0	0.727	217
7.0	0.728	253
8.0	0.729	290
9.0	0.730	326
10.0	0.731	363
11.0	0.733	400
12.0	0.734	437
13.0	0.736	475
14.0	0.738	513
15.0	0.740	551
16.0	0.742	589
17.0	0.744	628
18.0	0.747	667
19.0	0.749	706
20.0	0.752	746
21.0	0.755	787
22.0	0.758	828
23.0	0.762	869
24.0	0.765	912
25.0	0.769	954
26.0	0.773	998
27.0	0.777	1042
28.0	0.782	1088
29.0	0.786	1134
30.0	0.791	1181

the value of time for an angle half way between the integral values. The tables of x-distance and time as a function of a1 are referred to as UPX(a1) and UPT(a1).

In reference to figure 3.1

$$BY = PQ + BP \bullet SIN(c1) \tag{3.5}$$

$$BC = BY/COS(a2+c1) \tag{3.6}$$

$$CM = BC \bullet COS(a2) \tag{3.7}$$

$$BM = BC \bullet SIN(a2) \tag{3.8}$$

$$MD = CM \bullet TAN(a2+2c1) \tag{3.9}$$

$$CD = CM/COS(a2+2c1) \tag{3.10}$$

The x-distance travelled in the below-basement layer is

$$X' = BD = BM + MD \tag{3.11}$$

From 3.6, 3.7, 3.8, and 3.9

$$BD = BY[\{SIN(a2)+COS(a2) \bullet TAN(a2+2c1)\}/CCS(a2+c1)] \tag{3.12}$$

The travel time below the basement is

$$T' = BC/V1 + CD/V1 \tag{3.13}$$

From 3.6, 3.7 and 3.10

$$T' = BY/V1[\{1+COS(a2)/COS(a2+2c1)\}/COS(a2+c1)] \quad (3.14)$$

If we define the functions FX(c1,a2) and FT(c1,a2) to be the parts of equations 3.12 and 3.14 respectively within the curled brackets, { }, then

$$X' = BY \bullet FX(c1,a2) \quad (3.15)$$

$$T' = (BY/V) \bullet FT(c1,a2) \quad (3.16)$$

Values of the functions FX and FT can be tabulated for integral values of c1 and a2. For values of these angles in the range of interest, linear interpolation gives sufficient accuracy (1 msec) for non-integral values of the angles. Appendix A gives some sample values of these functions. Now, if we specify the velocity, V1, and incidence time, T1, then

$$PQ = V1 \bullet T1/2 \quad (3.17)$$

In addition,

$$BP = UPX(a1) \quad (3.18)$$

$$DT = UPX(b1) \quad (3.19)$$

But we know the velocity in the lowest layer above the basement, VL, and from Snell's law we can calculate a1 and b1.

$$a1 = \mathrm{ARCSIN}[VL \bullet \mathrm{SIN}(a2)/V1] \tag{3.20}$$

$$b1 = \mathrm{ARCSIN}[VL \bullet \mathrm{SIN}(a2+2c1)/V1] \tag{3.21}$$

The total x-distance and travel time are

$$X = X' + BP + DT \tag{3.22}$$

$$T = T' + \mathrm{UPT}(a1) + \mathrm{UPT}(b1) \tag{3.23}$$

It is apparent from equations 3.5 and 3.15 to 3.23 that if V1, T1 and c1 are specified then X and T depend only on a2. The program starts by calculating X for an estimated a2. If this X doesn't match the true shot-recorder distance, within a suitable distance (25 meters), then a new estimate of a2 is calculated based on the previous estimate and the error in X. After this iterative procedure has yielded the correct a2, the travel time for this path is calculated. This is done for all shot-recorder distances on a particular record. These time corrections are then used in calculating a coherency measure.

The coherency measure is calculated for a time gate centred about the time correction. Time gate width is twice

the value of the increment on incidence time. The coherency measure used here is

$$C = \frac{\mathrm{SUMt}\ [\mathrm{SUMi}\{f(i,t)\}]^2}{\mathrm{SUMt}\ [\mathrm{SUMi}\{|f(i,t)|\}]^2} \tag{3.24}$$

where SUMt is summation over t

SUMi is summation over i

i is the index on the number of traces

t is the time index within the time gate

f(i,t) represents the seismic trace

The numerator of equation 3.24 is a measure of the stacked energy within the time gate and the denominator is a measure of the value that the numerator would have if all traces being stacked were in-phase. C approaches zero for out of phase arrivals and one for in-phase arrivals.

By systematically varying V1, T1 and c1 one calculates the coherency measure as a function of the three variables and maxima indicate arrivals at particular values of V1, T1 and c1.

For the two layer case the argument is the same as for the one layer case except that now V1, T1 and c1 are known quantities from the previous calculation and the corresponding parameters V2, T2 and c2 in the second layer are varied. In a similar manner the argument could be extended to three layers. Appendix A ccntains the equations for the two-layer case and Appendix B has a listing of the

actual program.

CHAPTER 4

INTERPRETATION

4.1 Introduction

All of the data was plotted and examined for good reflections. The plotted records were usually filtered with a 5 to 30 Hz four pole Butterworth band-pass recursion filter (Shanks, 1967). As an example of a filtered record, figure 4.1 illustrates shot 1 from September 2. Each trace on this plot is normalized to the same maximum for plotting simplicity and the two segments have been normalized separately.

The velocity program used to analyze the data has been described in chapter 3, and the velocity model for the sedimentary section has been described in chapter 2. From figure 4.1 we can see that there are two prominent reflections at times of 7.5 and 10.7 seconds and a third weaker reflection at 11.7 seconds. These prominent reflections are common to most records and thus they have been chosen as the two layers to be used in the velocity model. An attempt was made to include a layer corresponding to the reflection at 11.7 seconds, but because of the poor resolution due to the large depth and the small horizontal displacements, the velocity analysis was inconclusive for this reflector. Although a velocity could not be obtained

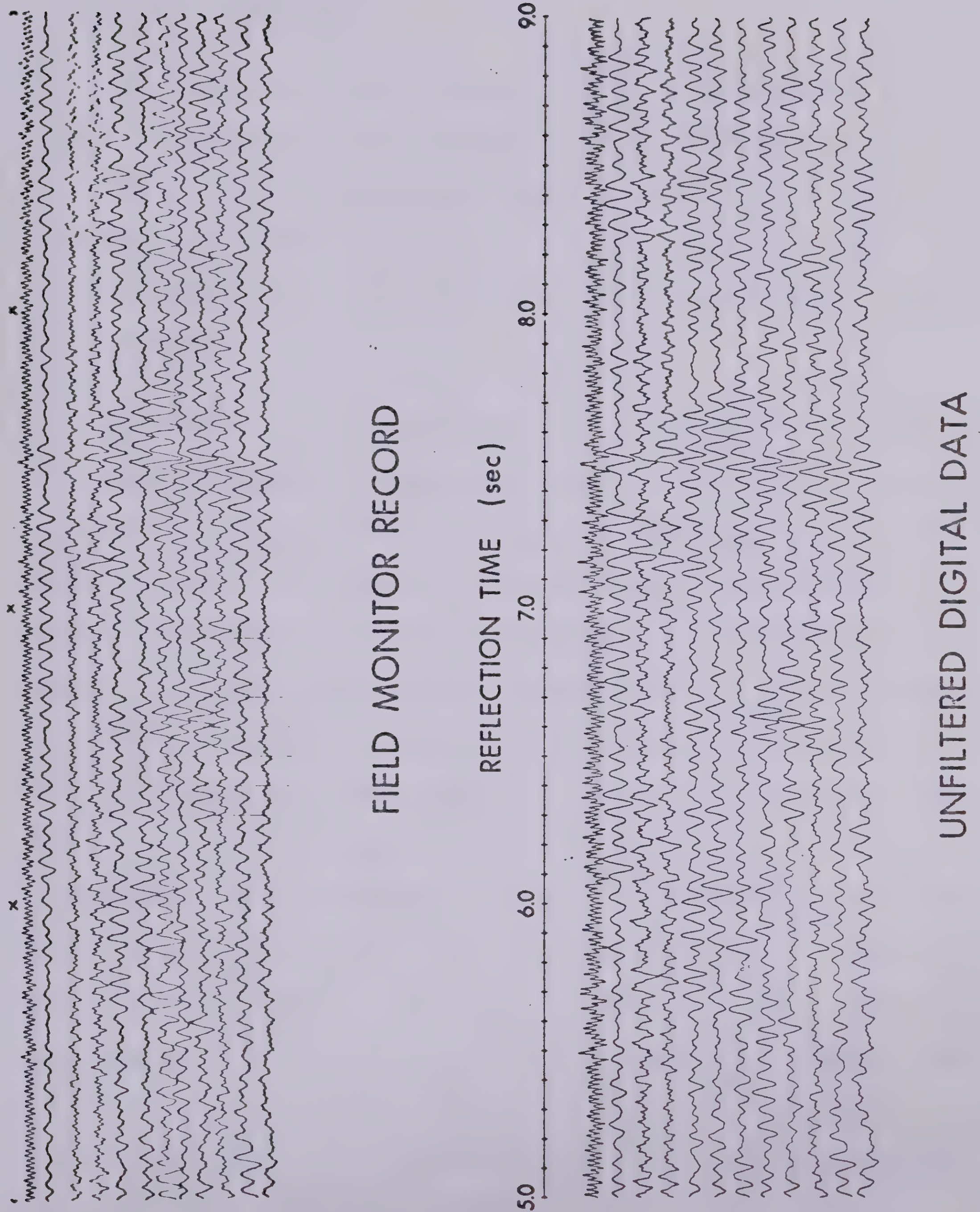


Figure 4.1 Sample filtered seismic record.

for the 11.7 second reflection, one can conclude that the deepest layer must range in thickness from 3 to 4 km for any reasonable velocity.

The records were checked for good reflections in the first 1.5 seconds, corresponding to the sedimentary section, so that a possible comparison could be made with a synthetic seismogram. Unfortunately, the gain settings used in recording the data were such that this section of the record was unusable.

Because of the suggestion of a low velocity layer in the upper basement by Sprenke (1972), it was felt that a careful analysis of the data in the appropriate time range should be made. A velocity spectra program as described by Taner and Koehler (1969) was applied to the data from the shots with small horizontal displacements. This program assumed horizontal layering. The results of this study indicated that prominent reflections to 3.5 seconds have RMS velocities in the range of 2.8 to 3.5 km/sec which are consistent with multiples from the sedimentary section. Using the velocity model for the sediments, a synthetic seismogram (Clowes, 1969) was produced. This synthetic seismogram showed multiples to 3.5 seconds and matched the field records reasonably well. For these two reasons it was felt that there is no justification in the present data for any suggested interfaces in this region of the crust.

For the above reasons, it was decided to construct a

two layer model of the crust. As an example of the output from the velocity program, table 4.1 and figure 4.2 are included. The table contains results obtained by running the velocity program on the 7.5 second reflection for shot 2 on September 2. These same results are shown as contours in the diagram in figure 4.2. The velocities are in km/sec and the times are two-way normal incidence times in seconds. The numbers in the table range from zero to one thousand depending on the coherency of the arrivals along various time corrections. From these results it can be seen that dip and velocity can not be completely separated, since increased dip results in a shift of the peak to higher velocity. To help improve on the interpretation, calculated travel times were printed by the velocity program for the various models. These are compared to times read from the records and this aids in the choice of a final model. For the example shown, the velocity and dip picks would be at 6.6 and 15 respectively.

4.2 The Two Layer Velocity Model

The September 2 data consisted of two groups of three shots at opposite ends of the spread. These shots were independently interpreted and the final model was based on the average of velocity and dip for each group. The three shots to the north gave a layer which dipped at 15 degrees to the south with velocity of 6.4 km/sec and two-way normal

TABLE 4.1

DIP = 13

TIME	VEL=5.70	5.80	5.90	6.00	6.10	6.20	6.30	6.40	6.50	6.60
5.72	328	250	300	272	246	241	187	160	129	100
5.74	350	441	527	508	431	435	357	359	283	346
5.76	601	600	648	566	508	520	570	537	541	518
5.78	626	612	536	635	789	782	716	687	678	688
5.80	545	567	820	827	819	880	752	658	714	622
5.82	541	545	763	700	825	723	760	812	853	824
5.84	573	603	648	509	677	871	845	864	825	785
5.86	402	450	617	669	719	739	752	681	751	620
5.88	596	637	608	544	591	612	544	603	613	698
5.90	564	469	574	529	591	603	565	632	702	605

DIP = 14

TIME	VEL=5.90	6.00	6.10	6.20	6.30	6.40	6.50	6.60	6.70	6.80
5.72	360	311	255	271	329	252	280	193	146	150
5.74	361	350	464	526	437	431	453	374	305	299
5.76	575	551	594	664	609	529	536	529	554	605
5.78	702	662	702	629	611	774	681	684	687	678
5.80	417	505	647	738	918	857	773	780	731	722
5.82	505	631	794	723	747	820	715	751	714	881
5.84	632	538	586	578	753	615	800	813	855	780
5.86	489	517	511	516	687	714	652	701	681	744
5.88	462	505	637	628	544	590	560	488	646	579
5.90	643	591	591	485	522	568	569	594	632	688

DIP = 15

TIME	VEL=6.20	6.30	6.40	6.50	6.60	6.70	6.80	6.90	7.00	7.10
5.72	390	321	247	237	270	288	236	193	187	164
5.74	344	413	521	585	458	446	418	401	337	327
5.76	575	677	630	529	609	593	489	499	571	529
5.78	673	691	702	730	677	711	681	718	688	737
5.80	521	626	610	733	918	858	808	755	797	667
5.82	549	631	753	723	742	813	679	751	695	821
5.84	577	583	537	602	671	615	740	813	884	759
5.86	447	484	464	513	628	674	721	752	681	714
5.88	578	633	568	644	627	590	599	574	627	579
5.90	618	561	588	452	522	580	577	632	676	702

DIP = 16

TIME	VEL=6.30	6.40	6.50	6.60	6.70	6.80	6.90	7.00	7.10	7.20
5.72	463	294	298	349	238	239	282	247	266	193
5.74	406	375	374	458	425	585	458	475	401	393
5.76	480	637	675	738	630	546	580	551	552	529
5.78	602	757	691	699	607	730	677	711	712	727
5.80	589	553	537	685	711	790	916	863	846	751
5.82	423	536	710	760	781	783	792	768	737	751
5.84	522	504	592	652	631	651	761	764	815	792
5.86	502	489	502	437	631	610	663	761	721	752
5.88	360	425	582	620	620	628	618	546	609	595
5.90	647	635	640	554	593	517	549	546	629	688

DIP = 17

TIME	VEL=6.30	6.40	6.50	6.60	6.70	6.80	6.90	7.00	7.10	7.20
5.72	283	396	511	424	347	346	265	287	232	282
5.74	367	464	431	358	372	470	464	425	517	502
5.76	387	373	433	512	602	691	575	644	546	584
5.78	224	433	649	634	782	699	693	526	695	700
5.80	475	564	515	565	628	640	629	869	850	852
5.82	345	397	468	577	533	693	753	734	883	788
5.84	387	456	465	591	632	604	640	736	564	634
5.86	445	496	535	521	505	573	427	559	651	702
5.88	413	434	339	460	608	558	656	651	632	587
5.90	332	497	583	535	635	659	554	504	524	597

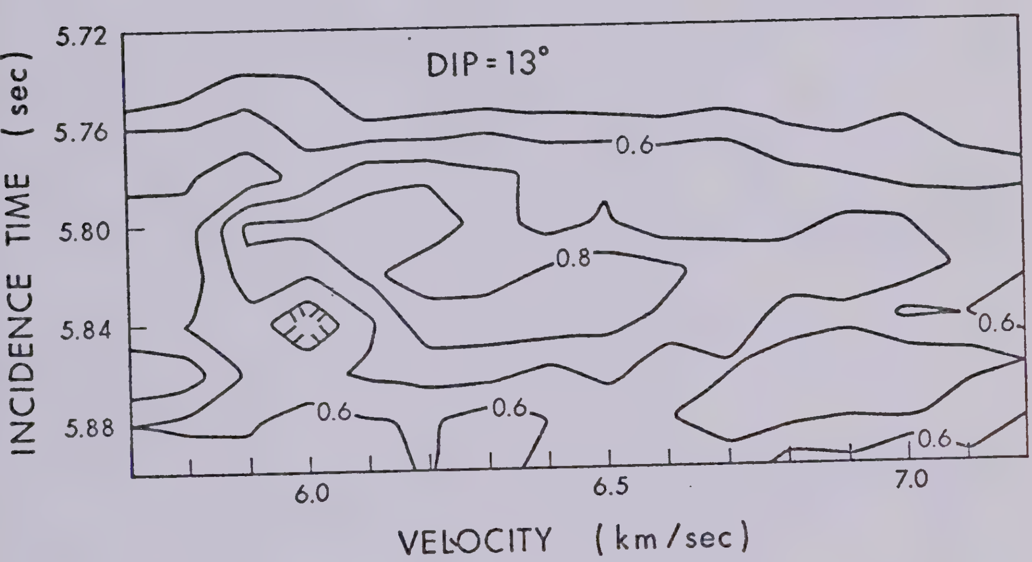
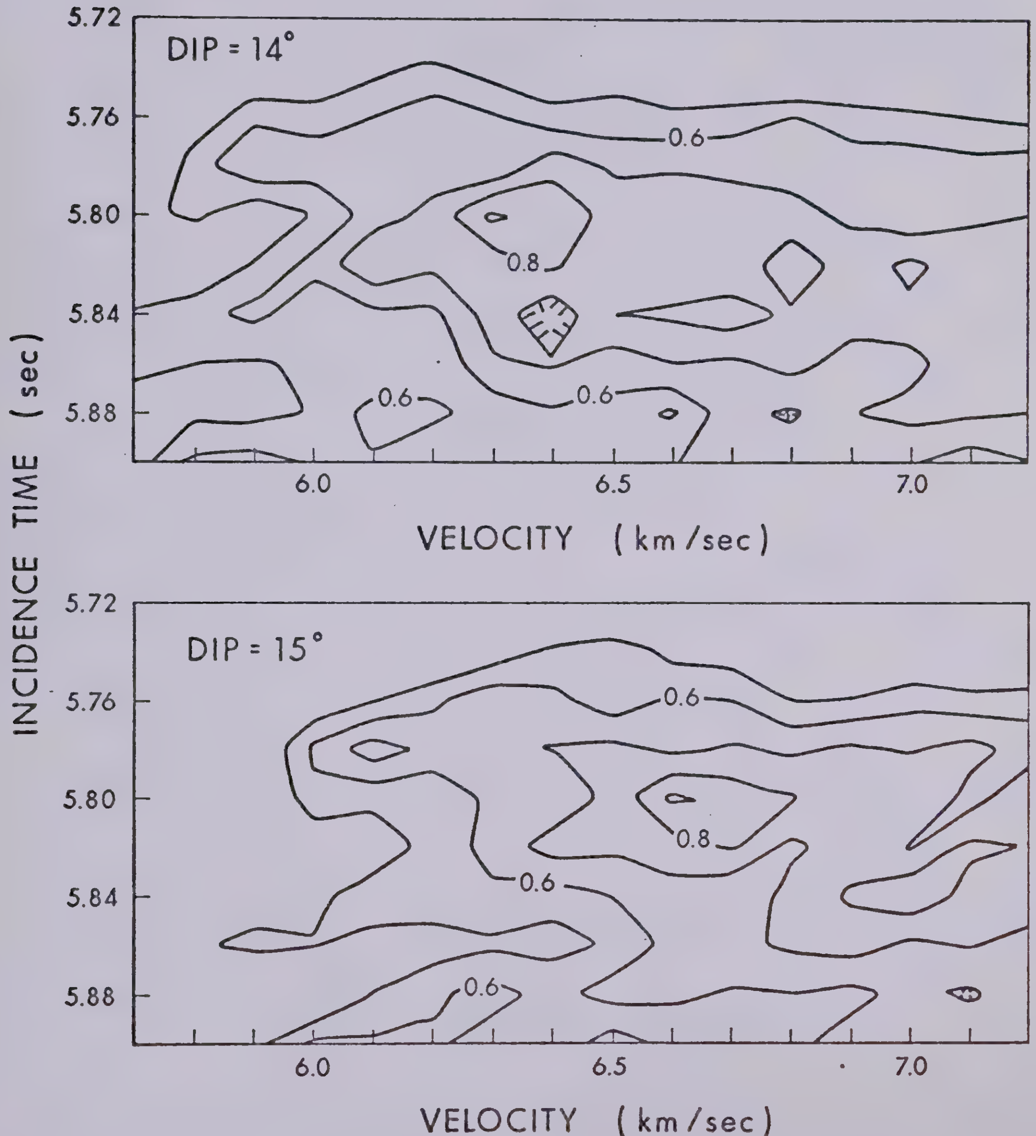
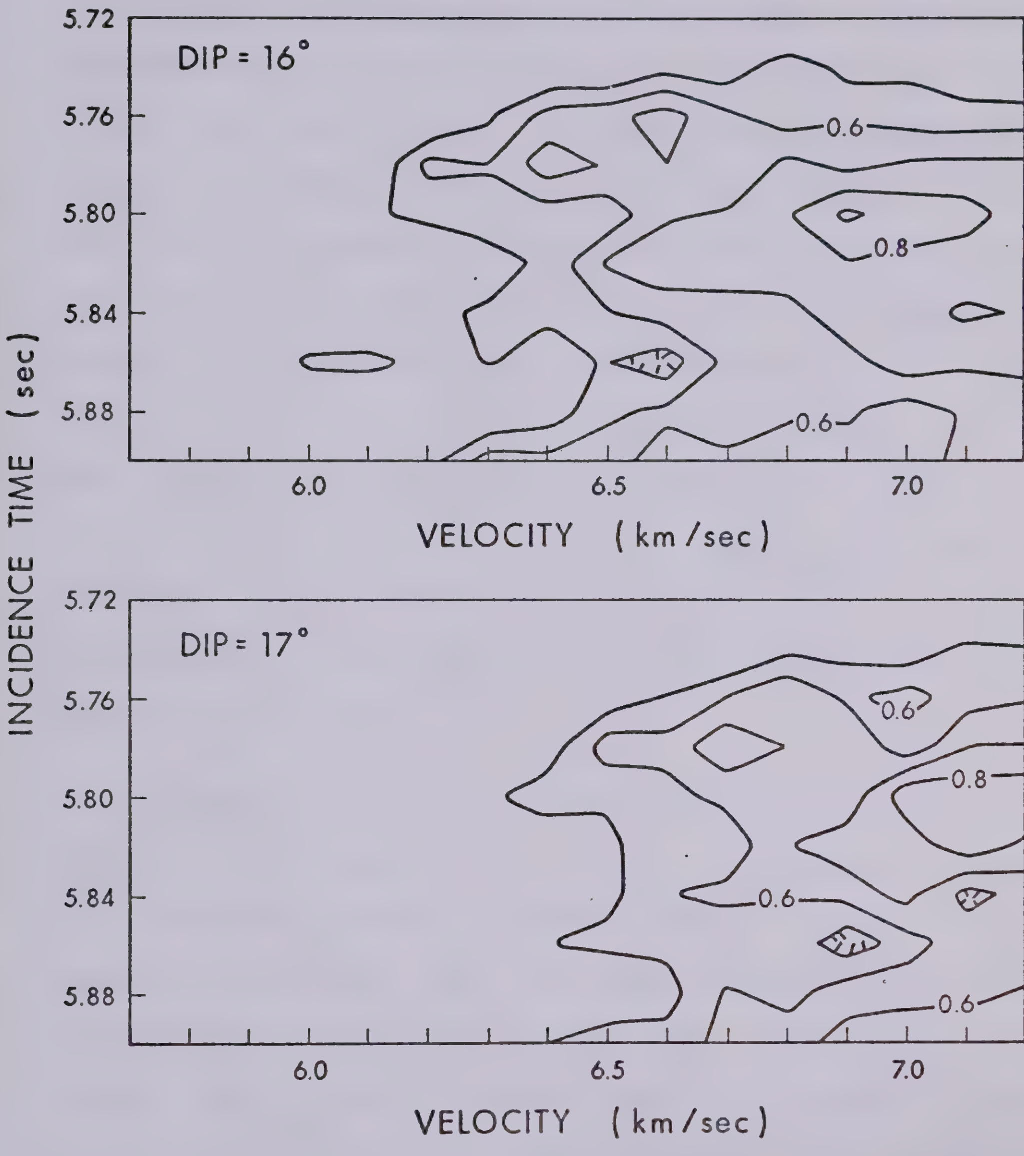


Figure 4.2 Contour diagram of velocity program results.



INCIDENCE TIME (sec)
DIP = 14°
5.72
5.76
5.80
5.84
5.88
0.6
0.8
6.0
6.5
7.0
VELOCITY (km/sec)
DIP = 15°
5.72
5.76
5.80
5.84
5.88
0.6
0.8
6.0
6.5
7.0
VELOCITY (km/sec)


DIP = 16°
5.72
5.76
5.80
5.84
5.88
0.6
0.8
0.6
6.0
6.5
7.0
VELOCITY (km/sec)
INCIDENCE TIME (sec)
DIP = 17°
5.72
5.76
5.80
5.84
5.88
0.6
0.8
0.6
0.6
6.0
6.5
7.0
VELOCITY (km/sec)

incidence time in this layer below shotpoint 2 of 5.8 seconds. The shots to the south led to a layer which dipped to the south at 18 degrees with a velocity of 6.3 km/sec and incidence time below shotpoint 5 of 5.69 seconds. No attempt has been made to phase correct the times to the beginning of the reflection. Estimated uncertainties are less than 2 degrees in dip, .2 km/sec in velocity, and .05 seconds in time. These uncertainties are consistent with scatter in individual determinations of dip and velocity. These two reflecting layers are shown in figure 4.3. The normal incidence times have been converted to depths and the horizons are plotted at the appropriate subsurface positions. It is obvious that the reflections are either from different discontinuities or that a fault exists in the reflecting interface.

Although velocity resolution was poor on the east-west profile, it was possible to choose a reasonable velocity from the above results. Dip must then be between 10 and 15 degrees to the east. This dip would introduce some error in interpreting the structure along the north-south profile because the velocity program makes the assumption that no dip is present in the east-west direction. It was felt that the data was not adequate enough to justify a correction for this effect.

Based on the results discussed in the previous paragraph, the second layer was added. The shots to the

south of the spread showed no clear reflection at the appropriate times, and hence the second layer is based only on the three shots to the north. The model obtained for this second layer has a velocity of 6.5 km/sec, a dip of 2 degrees to the south and an incidence time of 4.15 seconds in this layer under shotpoint 2. The uncertainties in these values would be slightly greater than in the values for the first layer because this layer depends on the previous results. This second layer is also shown in figure 4.3.

The above reflection was absent on the 7 traces at the north end of the recording spread for shot 3 and on the 3 traces at the north end for shot 2. This could be explained by the presence of a fault in the upper layer. The ray paths for the reflections which are absent would pass through the region of the fault and be obscured. This would substantiate the previous suggestion of a fault in this region.

4.3 Conclusion

The crustal model found for this area has shown the presence of steeply dipping interfaces within the deep crust and has suggested a possible fault. It would be desirable to have a continuous profile across the location of the suggested fault and greater offset distances would be advantageous for the deeper sections. Unfortunately, in this region the presence of pipe lines and power lines

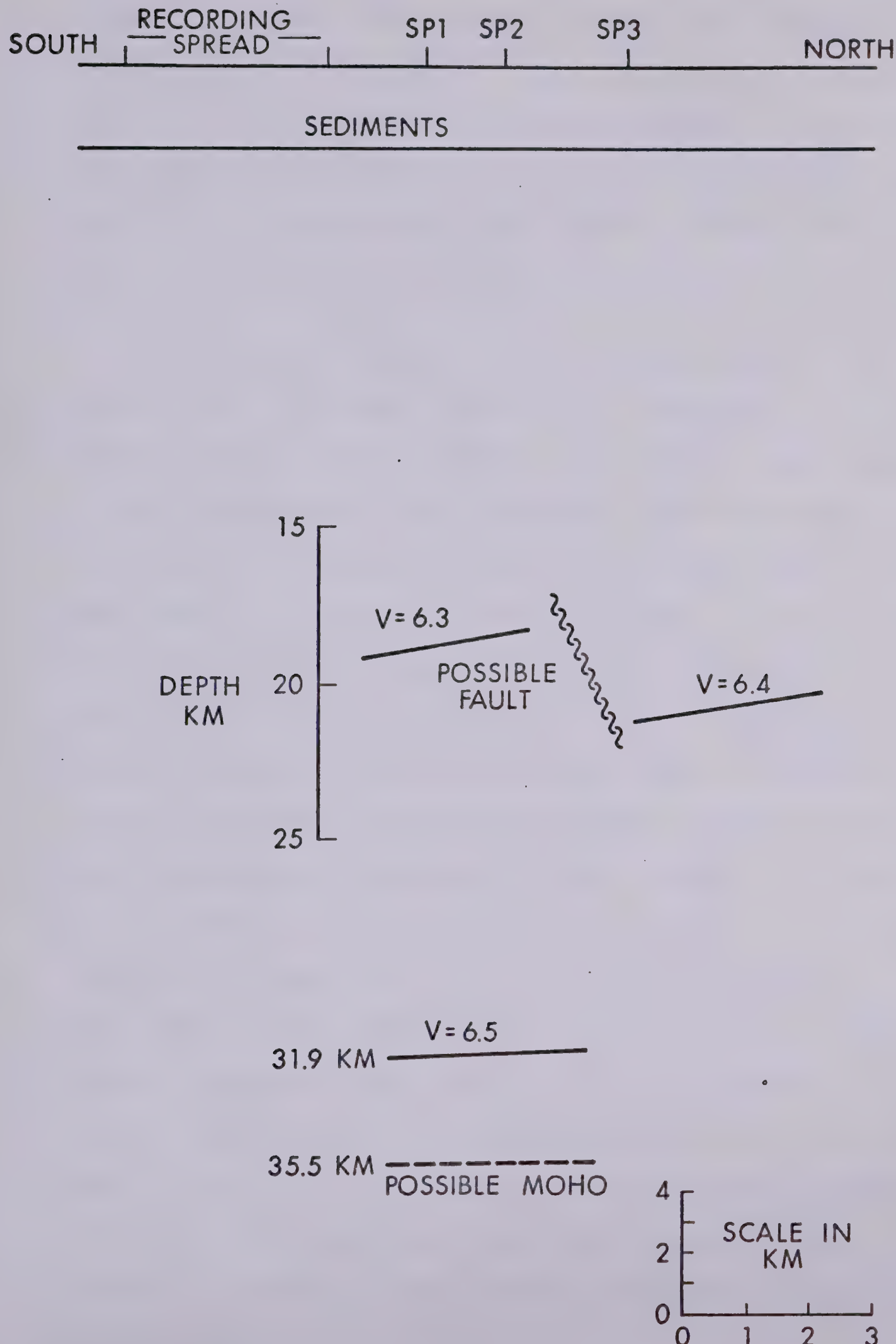


Figure 4.3 Crustal Model Diagram.

severely limits the areas of study. One solution to this problem might be the use of vibroseis methods; however, this might not have sufficient depth penetration to be useful. The presence of dipping layers within the basement suggests that P-coda results which were based on models consisting of flat crustal layers should be re-examined.

It is interesting to compare these results with those obtained in southern Alberta by Kanasewich and Cumming (1965), Clowes et al (1968) and Clowes and Kanasewich (1970). Kanasewich and Cumming (1965) mention a weak reflection at 8.4 seconds which is certainly less prominent than the 7.5 second reflection here. The 10.7 second reflection could be identified as the R discontinuity on the basis of its general appearance. This reflection is .7 seconds earlier than in the south which is consistent with the fact that the 7.5 second reflection is also earlier than the corresponding reflection in the south. If the 11.7 second reflection is interpreted as the Moho then the interval thickness from the R to M discontinuities is much less than in the southern part of the province. The total crustal thickness would then be 35.5 km, assuming a velocity in the lowest layer of 7.2 km/sec as found in the southern part of the province. This crustal thickness is less than in southern Alberta and the main reason would be the apparent thinning of the deepest layer between the R and M discontinuities.

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APPENDIX A

TWO LAYER VELOCITY PROGRAM

The derivation of the equations for the two layer velocity program is very similar to that for the one layer velocity program described in Chapter 3. In figure A.1 the ray path is ABCDEFG. PQ is normal to the first reflecting surface and is specified by V1 and T1. RS is normal to the second reflecting surface and R is directly below the shot point. V2, and T2 specify RS. The angle a3 is the variable used in iteratively solving for the ray path and all other angles can be found from it. Referring to figure A.1 and letting VL be the velocity in the lowest layer above the basement we have:

$$a2 = \mathrm{ARCSIN}\{V1 \bullet \mathrm{SIN}(a3)/V2\} - c1 \qquad (A.1)$$

$$a1 = \mathrm{ARCSIN}\{VL \bullet \mathrm{SIN}(a2)/V1\} \qquad (A.2)$$

$$b2 = \mathrm{ARCSIN}\{V1 \bullet \mathrm{SIN}(a3+2(c2-c1))/V2\} + c1 \qquad (A.3)$$

$$b1 = \mathrm{ARCSIN}\{VL \bullet \mathrm{SIN}(b2)/V1\} \qquad (A.4)$$

Now,

$$BP = \mathrm{UPX}(a1) \qquad (A.5)$$

$$FK = \mathrm{UPX}(b1) \qquad (A.6)$$

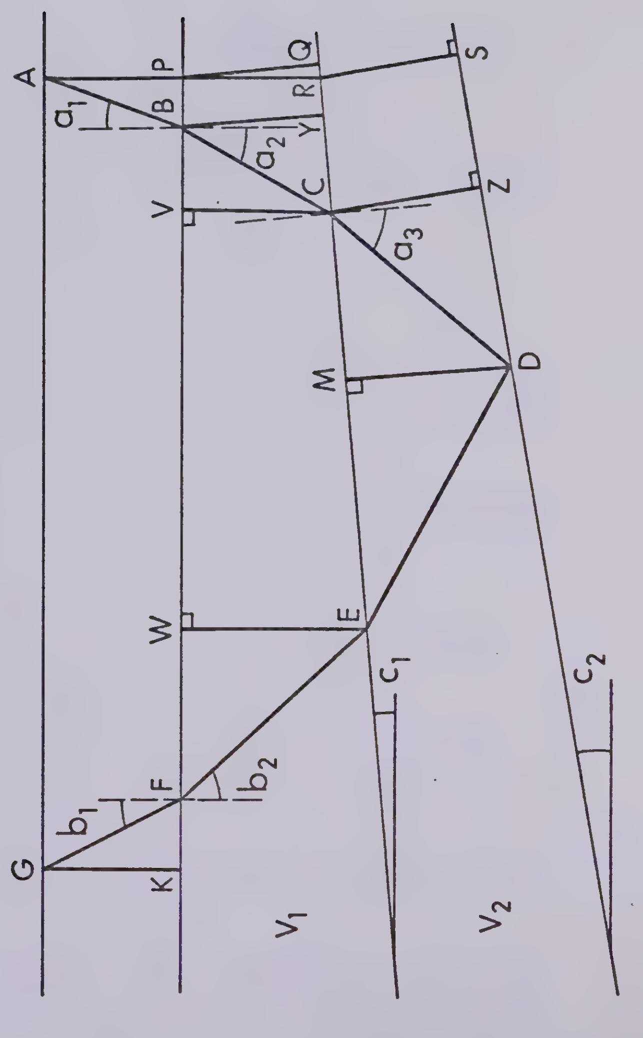

Figure A.1 Two layer model diagram.

Also, $$PQ = V1 \bullet T1/2 \tag{A.7}$$

$$BY = PQ + BP \bullet SIN(c1) \tag{A.8}$$

$$BC = BY/COS(a2+c1) \tag{A.9}$$

$$BV = BC \bullet SIN(a2) \tag{A.10}$$

$$CR = \{BP+BV\}/COS(c1) \tag{A.11}$$

$$RS = V2 \bullet T2/2 \tag{A.12}$$

$$CZ = RS + CR \bullet SIN(c2-c1) \tag{A.13}$$

$$CD = CZ/COS(a3+c2-c1) \tag{A.14}$$

$$DM = CD \bullet COS(a3) \tag{A.15}$$

$$CM = CD \bullet SIN(a3) \tag{A.16}$$

$$EM = DM \bullet TAN(a3+2(c2-c1)) \tag{A.17}$$

$$DE = DM/COS(a2+2(c2-c1)) \tag{A.18}$$

From A.14, A.15, A.16 and A.17

$$CE = \frac{CZ[SIN(a3) + COS(a3) \bullet TAN(a3+2(c2-c1))]}{COS(a3+c2-c1)} \tag{A.19}$$

Also, $$WV = CE \cdot COS(c1) \tag{A.20}$$

The travel time in the bottom layer is

$$T'' = CD/V2 + DE/V2 \tag{A.21}$$

From A.14, A.15 and A.18

$$T'' = \frac{CZ[1 + COS(a3)/COS(a3+2(c2-c1))]}{V2 \cdot COS(a3+c2-c1)} \tag{A.22}$$

Recalling the definitions of FX and FT in 3.12 and 3.14

$$CE = CZ \cdot FX(c2-c1,a3) \tag{A.23}$$

$$T'' = [CZ/V2] \cdot FT(c2-c1,a3) \tag{A.24}$$

Now, $$EW = PQ/COS(c1) + (BP+BV+WV) \cdot TAN(c1) \tag{A.25}$$

$$EF = EW/COS(b2) \tag{A.26}$$

$$FW = EW \cdot TAN(b2) \tag{A.27}$$

But, the x-distance is

$$X = BP + BV + WV + FW + FK \tag{A.28}$$

and the travel time is

$$T = UPT(a1) + UPT(b1) + (BC+EF)/V1 + T'' \qquad (A.29)$$

From equations A.1 to A.13, A.20, A.23, A.25, A.27 and A.28 it is clear that when V2, T2 and c2 are fixed along with V1, T1 and c1, then X is a function of only a3. For any value of X it is possible to calculate the travel time for the corresponding path according to equations A.1 to A.13, A.20, A.23 to A.26 and A.29. Thus, in the two layer case one can solve iteratively for the value of a3 which gives the proper x-distance. This can be done for all shot-recorder distances on a record and time corrections can be calculated for each trace in the same way as for the one layer case.

Table A.1 which follows gives values of the functions FX and FT for values of c2-c1 within the range of interest.

TABLE A.1

c2-c1 = -20

a3(deg)	FX	FT
20.0	0.0	2.0000
21.0	0.0369	1.9877
22.0	0.0734	1.9761
23.0	0.1095	1.9653
24.0	0.1451	1.9551
25.0	0.1805	1.9457
26.0	0.2155	1.9369
27.0	0.2502	1.9288
28.0	0.2846	1.9214
29.0	0.3187	1.9146
30.0	0.3527	1.9084
31.0	0.3864	1.9028
32.0	0.4199	1.8979
33.0	0.4533	1.8935
34.0	0.4865	1.8897
35.0	0.5196	1.8866
36.0	0.5526	1.8840
37.0	0.5855	1.8820
38.0	0.6184	1.8805
39.0	0.6512	1.8797
40.0	0.6840	1.8794
41.0	0.7168	1.8797
42.0	0.7497	1.8805
43.0	0.7825	1.8820
44.0	0.8155	1.8840
45.0	0.8485	1.8866
46.0	0.8816	1.8897
47.0	0.9148	1.8935
48.0	0.9482	1.8979
49.0	0.9817	1.9028
50.0	1.0154	1.9084

c2-c1 = -10

a3(deg)	FX	FT
10.0	0.0	2.0000
11.0	0.0353	1.9942
12.0	0.0705	1.9890
13.0	0.1055	1.9844
14.0	0.1403	1.9805
15.0	0.1750	1.9771
16.0	0.2096	1.9744
17.0	0.2441	1.9723
18.0	0.2785	1.9708
19.0	0.3129	1.9699
20.0	0.3473	1.9696
21.0	0.3817	1.9699
22.0	0.4161	1.9708
23.0	0.4505	1.9723
24.0	0.4850	1.9744
25.0	0.5196	1.9771
26.0	0.5543	1.9805
27.0	0.5891	1.9844
28.0	0.6241	1.9890
29.0	0.6593	1.9942
30.0	0.6946	2.0000
31.0	0.7302	2.0065
32.0	0.7660	2.0136
33.0	0.8020	2.0214
34.0	0.8384	2.0299
35.0	0.8751	2.0391
36.0	0.9121	2.0490
37.0	0.9495	2.0596
38.0	0.9873	2.0710
39.0	1.0255	2.0831
40.0	1.0642	2.0960

c2-c1 = 0

a3(deg)	FX	FT
0.0	0.0	2.0000
1.0	0.0349	2.0003
2.0	0.0698	2.0012
3.0	0.1048	2.0027
4.0	0.1399	2.0049
5.0	0.1750	2.0076
6.0	0.2102	2.0110
7.0	0.2456	2.0150
8.0	0.2811	2.0197
9.0	0.3168	2.0249
10.0	0.3527	2.0309
11.0	0.3888	2.0374
12.0	0.4251	2.0447
13.0	0.4617	2.0526
14.0	0.4987	2.0612
15.0	0.5359	2.0706
16.0	0.5735	2.0806
17.0	0.6115	2.0914
18.0	0.6498	2.1029
19.0	0.6887	2.1152
20.0	0.7279	2.1284
21.0	0.7677	2.1423
22.0	0.8081	2.1571
23.0	0.8489	2.1727
24.0	0.8905	2.1893
25.0	0.9326	2.2068
26.0	0.9755	2.2252
27.0	1.0191	2.2447
28.0	1.0634	2.2651
29.0	1.1086	2.2867
30.0	1.1547	2.3094

c2-c1 = 10

a3(deg)	FX	FT
-10.0	0.0	2.0000
-9.0	0.0356	2.0065
-8.0	0.0714	2.0136
-7.0	0.1074	2.0214
-6.0	0.1438	2.0299
-5.0	0.1805	2.0391
-4.0	0.2175	2.0490
-3.0	0.2549	2.0596
-2.0	0.2927	2.0710
-1.0	0.3309	2.0831
0.0	0.3696	2.0960
1.0	0.4088	2.1097
2.0	0.4485	2.1243
3.0	0.4888	2.1397
4.0	0.5296	2.1560
5.0	0.5711	2.1732
6.0	0.6133	2.1914
7.0	0.6563	2.2106
8.0	0.7000	2.2307
9.0	0.7445	2.2520
10.0	0.7899	2.2743
11.0	0.8362	2.2978
12.0	0.8835	2.3225
13.0	0.9318	2.3485
14.0	0.9812	2.3758
15.0	1.0318	2.4045
16.0	1.0837	2.4346
17.0	1.1369	2.4662
18.0	1.1915	2.4995
19.0	1.2477	2.5344
20.0	1.3054	2.5711

c2-c1 = 20

a3(deg)	FX	FT
-20.0	0.0	2.0000
-19.0	0.0374	2.0131
-18.0	0.0753	2.0270
-17.0	0.1137	2.0417
-16.0	0.1527	2.0572
-15.0	0.1923	2.0737
-14.0	0.2326	2.0910
-13.0	0.2736	2.1093
-12.0	0.3152	2.1285
-11.0	0.3577	2.1488
-10.0	0.4010	2.1701
-9.0	0.4452	2.1926
-8.0	0.4903	2.2161
-7.0	0.5364	2.2409
-6.0	0.5836	2.2669
-5.0	0.6319	2.2943
-4.0	0.6814	2.3230
-3.0	0.7322	2.3532
-2.0	0.7843	2.3850
-1.0	0.8379	2.4183
0.0	0.8930	2.4534
1.0	0.9497	2.4902
2.0	1.0082	2.5290
3.0	1.0685	2.5697
4.0	1.1309	2.6127
5.0	1.1953	2.6579
6.0	1.2621	2.7055
7.0	1.3314	2.7557
8.0	1.4032	2.8087
9.0	1.4779	2.8647
10.0	1.5557	2.9238

APPENDIX B

LISTING OF VELOCITY PROGRAM

This appendix lists the actual velocity program. Table B.1 lists the correspondence between variables used in this thesis and the variable name in the program.

The program is in Fortran and for maximum efficiency should be compiled using the IBM Fortran H compiler with the optimization level set at 2. A typical run for 12 seismic traces with 20 different velocities, 10 different incidence times, 5 different dip angles and a time gate width of .1 seconds required approximately 15 seconds on an IBM 360/67 computer.

TABLE B.1

THESIS VARIABLE	PROGRAM VARIABLE NAME
UPT	UPFUNT
UPX	UPFUNX
FX	FUNAD
FT	FUNAED
a1	ALPHA1
b1	BETA1
a2	ALPHA(1,I)
a3	ALPHA(2,I)
b2	BETA(1,I)
c1	THETA1 or THETA for 1 layer
c2	THETA (2 layer case)
V1	V1 or V for 1 layer case
V2	V for 2 layer case
T1	T1 or T0 for 1 layer case
T2	T0 for 2 layer case

```
C*****************************************************************
C**********     TWO LAYER VELOCITY PROGRAM     *************
C*****************************************************************
C
C
C        THE PURPOSE OF THIS PROGRAM IS TO TEST A SET OF 12
C     SEISMIC TRACES FOR AN ARRIVAL OF A SIGNAL WITH A
C     PARTICULAR STEPOUT IN TIME FRCM TRACE TO TRACE. THE
C     FACTORS AFFECTING STEPOUT ARE DIP VELOCITY, AND
C     DEPTH OF REFLECTOR.
C
C
C        THE PROGRAM IS DESIGNED UPON THE ASSUMPTION THAT A
C     KNOWN FLAT LAYERED MODEL EXISTS ABOVE THE BASEMENT AND
C     THAT WE WILL LOCK FOR NO MORE THAN 2 LAYERS BELOW THE
C     BASEMENT. EACH OF THESE 2 LAYERS IS FOUND BY A SEPERATE
C     RUN OF THE PROGRAM STARTING WITH THE LAYER JUST BELOW
C     THE BASEMENT AND GOING DEEPER ON EACH SUCCESSIVE RUN.
C     WHEN WORKING ON THE SECOND LAYER BELOW THE BASEMENT THE
C     RESULTS OF THE FIRST LAYER ARE NEEDED. THE QUANTITIES
C     V, THETA, AND TO IN THE UNKNOWN LAYER ARE VARIED AND
C     TIME CORRECTIONS ARE CALCULATED FOR EACH TRACE FOR EACH
C     DIFFERENT SET OF V, THETA, AND TO.
C
C              V = INTERVAL VELOCITY IN LAST LAYER
C              THETA = DIP OF LAST LAYER
C              TO = TWO WAY TRAVEL TIME ALONG A PATH IN THE
C                   LAST LAYER PERPENDICULAR TO THE INTER-
C                   FACE AT THE BOTTOM OF THIS LAYER AND
C                   FROM A POINT DIRECTLY BELOW THE SHOT.
C
C
C        THE ARRAYS UPFUN, UPFUNT, FUNAD, AND FUNAED ARE
C     REQUIRED. THESE ARE USUALLY STORED ON A DISK (IN THIS
C     CASE LOGICAL UNIT 1).
C
C
C        UPFUN(61) CONTAINS THE X-DISTANCE (DISTANCE ALONG
C     GROUND FROM SHOT POINT) WHICH A SEISMIC RAY TRAVELS FOR
C     A GIVEN ANGLE BETWEEN THE RAY AND THE PERPENDICULAR TO
C     THE INTERFACE IN THE LAYER ABOVE BASEMENT. THE ANGLE
C     CAN RANGE FROM -30 TO 30 DEGREES AND X VALUES ARE GIVEN
C     IN UPFUN FOR ALL INTEGER VALUES IN THIS RANGE. EXACT
C     VALUES ARE FOUND BY INTERPOLATICN.
C
C
C        UPFUNT(61) IS SIMILAR TO UPFUN ONLY IT CONTAINS
C     THE TRAVEL TIMES TAKEN BY THE RAY ABOVE THE BASEMENT.
C     IN THIS CASE INTERPOLATION IS NOT USED BECAUSE
C     TRUNCATION IS ACCURATE ENOUGH. UPFUN(1) IS THE TIME FOR
C     AN ANGLE OF - 30.5, UPFUN(2) FOR -29.5 ... UPFUN(31)
C     FOR -.5 OR .5 AS BOTH ARE EQUAL, UPFUN(32) FOR 1.5 ETC.
C
C
```

```
C         FUNAD(I,J) CONTAINS VALUES SUCH THAT FUNAD(I,J)
C     MULTIPLIED BY THE THICKNESS (PERPENDICULAR TO BOTTOM OF
C     LAST LAYER) OF LAST LAYER AT THE POINT THE RAY ENTERS
C     THE LAST LAYER EQUALS THE X-DISTANCE TRAVELLED IN THE
C     BOTTOM LAYER. THE I INDEX IS THE INDEX ON THE DIP
C     ANGLE. IF THETA IS THE DIP OF THE BOTTOM LAYER AND
C     THETA1 IS THE DIP OF THE LAYER ABOVE IT THEN I=1
C     REPRESENTS (THETA-THETA1) EQUAL TO -20 AND I=2 IS
C     (THETA-THETA1) EQUAL -19 ETC. THETA AND THETA1 MUST
C     TAKE ON INTEGRAL VALUES. THE J INDEX IS THE INDEX ON
C     THE ANGLE THAT THE RAY MAKES WITH THE NORMAL WHEN IT
C     ENTERS THE BOTTOM LAYER. J=1 IS A VALUE OF THIS ANGLE
C     EQUAL TO - (THETA-THETA1) AND J=2 IS 1-(THETA-THETA1)
C     ETC. INTERPOLATION CAN BE USED. NOTE THAT IF SHOTS ARE
C     SHOT IN AN UPDIP DIRECTION THEN THETA IS NEGATIVE.
C
C
C         FUNAED(I,J) IS SIMILAR TO FUNAD ONLY FUNAED(I,J)
C     MULTIPLIED BY 1/V TIMES THE MULTIPLYING FACTOR FOR
C     FUNAD(I,J) GIVES THE TRAVEL TIME IN THE BOTTOM LAYER.
C
C
C         USING THESE ARRAYS AND A GIVEN V, THETA, AND TO IT
C     IS POSSIBLE TO CALCULATE A TIME CORRECTION FOR EACH
C     TRACE WITH ITS PARTICULAR X-DISTANCE.
C
C
C         V, THETA, AND TO ARE ALL VARIED IN AN ATTEMPT TO
C     FIND THE VALUES WHICH BEST FIT THE PARTICULAR
C     REFLECTION ON THE RECORD. AS A MEASURE OF GOODNESS OF
C     THE FIT THE FOLLOWING IS CALCULATED:
C
C              SUM(T) = SUM OF F(T) OVER ALL TRACES INSIDE
C                       A TIME WINDOW CENTRED ABOUT THE TIME
C                       CORRECTION.  THE WINDOW WIDTH IS
C                       TWICE THE INCREMENT ON TO.
C
C              SUMNOR(T)  = SAME AS ABOVE ONLY ONE USES
C                           ABSOLUTE VALUE OF F(T). F(T) IS
C                           THE SEISMIC SIGNAL AS A FUNCTION
C                           OF TIME.
C
C         THEN SUMX = SUM OVER T OF SUM(T)**2
C              SUMNX = SUM OVER T OF SUMNOR(T)**2
C
C
C         SUMX IS A MEASURE OF THE TOTAL STACKED ENERGY
C     COMING THROUGH THE WINDOW. SUMNX IS A MEASURE OF WHAT
C     THE TOTAL STACKED ENERGY WOULD BE IF ALL TRACES BEING
C     STACKED WERE PERFECTLY IN-PHASE. THE QUANTITY
C     1000*SUMX/SUMNX WILL APPROACH ZERO FOR RANDOM ARRIVALS
C     AND WILL APPROACH 1000 IF ALL ARRIVALS ALONG THE TIME
C     CORRECTION ARE IN PHASE.
C
```

```
C
      DIMENSION UPFUN(61),UPFUNT(61),FUNAD(45,31),FUNAED(45,31)
      DIMENSION A(500,12),X(12),TCOR(12),ALPHA(2,12),BETA(2,12)
      DIMENSION ISPEC(20),SUM(40),SUMNOR(40),TITLE(20),VEL(20)
C****
C    TITLE = TITLE OF THIS RUN
C    NUMTR = NUMBER OF TRACES FOR THIS RUN
C    IP = POINT IN ARRAY ON TAPE THAT WE WANT AS FIRST POINT
C         OF 500 FOR SEISMIC TRACES STORED IN A
C    LAYNUM = NUMBER OF LAYER (BELOW BASEMENT) BEING SOLVED
C    V1 = VELOCITY IN FIRST LAYER BELOW BASEMENT
C    T1 = TO VALUE FOUND FOR FIRST LAYER BELOW BASEMENT
C    ITHET1 = DIP OF FIRST LAYER BELOW BASEMENT
C    X = ARRAY OF X-DISTANCES OF GEOPHONES
C    TINIT = INITIAL TO VALUE
C    TIMINC = INCREMENT ON TO
C    NTIME = NUMBER OF TO VALUES TO BE USED
C    VINIT = INITIAL VELOCITY VALUE
C    VELINC = VELOCITY INCREMENT
C    NVEL = NUMBER OF VELOCITY VALUES TO USE
C    ITHETA = INITIAL VALUE OF DIP ANGLE
C    ITHINC = INCREMENT ON THETA
C    NTHETA = NUMBER OF THETA VALUES TO USE
C****
      READ (5,1) TITLE
      READ (5,2) NUMTR,IP,LAYNUM,V1,T1,ITHET1
      READ (5,3) X
      READ (5,4) TINIT,TIMINC,NTIME,VINIT,VELINC,NVEL,ITHETA
     .,ITHINC,NTHETA
      NGATE=357.1428*TIMINC+.5
      IF (NGATE.GT.40) STOP 1
      IF (NVEL.GT.20) STOP 2
      IF (LAYNUM.GT.2) STOP 3
      WRITE (6,8) TITLE,(X(I),I=1,NUMTR)
      WRITE (6,9) LAYNUM
      GO TO (44,43),LAYNUM
   43 WRITE (6,10) V1,T1,ITHET1
      THETA1=ITHET1/57.29578
      STH1=SIN(THETA1)
      CTH1=SQRT(1.-STH1**2)
      VT21=V1*T1/2.0
      GO TO 45
   44 ITHET1=0
   45 VEL(1)=VINIT
      DO 50 I=2,NVEL
   50 VEL(I)=VEL(I-1)+VELINC
      READ (1) UPFUN,UPFUNT,FUNAD,FUNAED
C****
C    RGET READS IN SEISMIC TRACES OFF TAPE INTO A(500,12)
C    WITH A(1,I) EQUAL TO THE IP'TH POINT OF THE I'TH TRACE
C    WHERE THE TRACE ON TAPE IS ASSUMED TO HAVE POINT 1 AT
C    TIME ZERO
C****
      CALL RGET(2,11208,A,500,NUMTR,IP,0,&999)
```

```
C****
C     THREE LOOPS FOLLOW:
C          ICT1 IS LOOP IN WHICH THETA IS VARIED
C          ICT2 IS LOOP IN WHICH TO IS VARIED
C          ICT3 IS LOOP IN WHICH V IS VARIED
C
C     ALPHA REFERS TO ANGLE BETWEEN RAY AND NORMAL FOR
C          DOWNGCING RAYS.
C     ALPHA(I,J) = ANGLE AT TOP OF I'TH LAYER BELOW BASEMENT
C          FOR J'TH TRACE
C     BETA IS SAME AS ALPHA ONLY FOR UPGOING RAYS
C     ALPHA1 AND BETA1 ARE ANGLES IN LAYER ABOVE BASEMENT
C     XP = X DISTANCE TRAVELLED BY RAY BEING CONSIDERED
C****
      DO 500 ICT1=1,NTHETA
      THETA=ITHETA/57.29578
      STH=SIN(THETA)
      CTH=SQRT(1.-STH**2)
      STHM1=SIN(THETA-THETA1)
      I1=ITHETA-ITHET1+21
      IF (I1.GT.45.OR.I1.LT.1) STOP 4
      TO=TINIT
      WRITE (6,5) TITLE,ITHETA
      WRITE (6,6) (VEL(I),I=1,NVEL)
      DO 400 ICT2=1,NTIME
      V=VINIT
      DO 300 ICT3=1,NVEL
      VT2=V*TO/2.0
C****
C     COMPUTED GO TO BRANCHES TO 2 PLACES DEPENDING CN NUMBER
C     OF LAYERS INVOLVED.  THESE 2 CASES WERE CODED SEPARATELY
C     AND THEREFORE ARE NOT COMBINED AT ALL.  THEY PROBABLY
C     COULD BE CCMBINED TO SOME EXTENT TO REDUCE CODING
C     AND STORAGE.  TO SAVE STORAGE ONE CAN JUST CMIT THE
C     TWC UNUSED SECTIONS WHEN COMPILING.
C
C     DUE TO A BUG IN THE FORTRAN H COMPILER THESE 2 SECTIONS
C     CAN NOT BE COMPILED TOGETHER.  TO COMPILE ONE LAYER AT
C     A TIME REPLACE STATEMENT 110 OR 140 BY STOP 110 OR STOP
C     140 STATEMENTS AND LEAVE OUT THE ENTIRE SECTION.
C****
      GO TO (110,140),LAYNUM
C****
C     THIS SECTION IS FOR THE ONE LAYER CASE
C     4.874 IS VELOCITY IN LOWEST OF UPPER LAYERS
C****
  110 VCV=4.874/V
C****
C     CALCULATE A FIRST APPROXIMATION TO ALPHA(1,1)
C****
      FALPHA=X(1)/VT2
      DO 115 J=1,31
      IF (FALPHA.LT.FUNAD(I1,J)) GO TO 116
  115 CONTINUE
```

```
      STOP 11
  116 IALP=J-2-ITHETA
      ALPHA(1,1)=IALP/57.29578
      DELTA=0.0
C****
C     LOOP ON I IS FOR NUMBER OF TRACES
C     LOOP ON J IS FOR 10 ITERATIONS IN AN ATTEMPT TO FIND
C****                                                  RAY PATH
      DO 130 I=1,NUMTR
      DO 120 J=1,10
      $=VOV*SIN(ALPHA(1,I))
      ALPHA1=ARSIN($)
      BETA(1,I)=ALPHA(1,I)+2.0*THETA
      $=VOV*SIN(BETA(1,I))
      BETA1=ARSIN($)
      ALPH1D=57.29578*ALPHA1
      IALP1=ALPH1D
      I$=IALP1+31
      $=ALPH1D-IALP1
      INDEX=I$
      IF (ALPHA1.LT.0.0) INDEX=INDEX-1
      IF (INDEX.GT.60.OR.INDEX.LT.1) STOP 12
      XP=UPFUN(I$)+$*(UPFUN(INDEX+1)-UPFUN(INDEX))
      I2=IALP+1+ITHETA
      INDEXS=I2
      IF (ALPHA(1,I).LT.0.0) INDEXS=I2-1
      IF (INDEXS.GT.30.OR.INDEXS.LT.1) STOP 13
      AITDIV=(FUNAD(I1,INDEXS+1)-FUNAD(I1,INDEXS))
      FUNAD1=FUNAD(I1,I2)+DELTA*AITDIV
      PATHNI=VT2+XP*STH
      TIMENI=PATHNI/V
      XP=XP+FUNAD1*PATHNI
      BETA1D=BETA1*57.29578
      IBETA1=BETA1D
      I$=IBETA1+31
      $=BETA1D-IBETA1
      INDEX=I$
      IF (BETA1.LT.0.0) INDEX=INDEX-1
      IF (INDEX.GT.60.OR.INDEX.LT.1) STOP 14
      XP=XP+UPFUN(I$)+$*(UPFUN(INDEX+1)-UPFUN(INDEX))
      $=XP-X(I)
      IF (ABS($).LT.0.025) GO TO 125
C****
C     CALCULATE A NEXT APPROXIMATION TO ALPHA(1,I)
C****
      ALPHA(1,I)=ALPHA(1,I)-$/XP*FUNAD1/AITDIV/57.29578
      IALP=ALPHA(1,I)*57.29578
  120 DELTA=ALPHA(1,I)*57.29578-IALP
      STOP 15
C****
C     CALCULATE TCOR(I)=TIME CORRECTION ON I'TH TRACE AND
C     ALSO CALCULATE A FIRST APPROXIMATION TO ALPHA(1,I)
C     FOR NEXT I VALUE
C****
```

```
  125 TCOR(I)=TIMENI*(FUNAED(I1,I2)+DELTA*(FUNAED(I1,INDEXS+
     .1)-FUNAED(I1,INDEXS)))
      TCOR(I)=TCOR(I)+UPFUNT(IBETA1+31)+UPFUNT(IALP1+31)
      IF (I.EQ.NUMTR) GO TO 200
      ALPHA(1,I+1)=ALPHA(1,I)+(X(I+1)-X(I))/X(I)*FUNAD1/AITD
     .IV/57.29578
      IALP=ALPHA(1,I+1)*57.29578
      DELTA=ALPHA(1,I+1)*57.29578-IALP
  130 CONTINUE
      STOP 16
C
C****
C    STATEMENT 140 STARTS THE 2 LAYER CASE
C****
C
  140 VOV=4.874/V1
C**** 4.874 IS THE VELOCITY IN LOWEST OF UPPER LAYERS
      V1OV=V1/V
C****
C    CALCULATE A FIRST APPROXIMATION TO ALPHA(2,1)
C****
      APFACT=VT2/(VT2+VT21)
      FALPHA=X(1)/VT2*APFACT
      DO 145 J=1,31
      IF (FALPHA.LT.FUNAD(I1,J)) GO TO 146
  145 CONTINUE
      STOP 21
  146 IALP=J-2-ITHETA+ITHET1
      ALPHA(2,1)=IALP/57.29578
      DELTA=0.0
C****
C    LOOP ON I IS FOR NUMBER OF TRACES
C    LOOP ON J IS FOR 10 ITERATIONS IN AN ATTEMPT TO FIND
C         RAY PATH
C****
      DO 160 I=1,NUMTR
      DO 150 J=1,10
      $=V1OV*SIN(ALPHA(2,I))
      ALPHA(1,I)=ARSIN($)-THETA1
      $=VOV*SIN(ALPHA(1,I))
      ALPHA1=ARSIN($)
      BETA(2,I)=ALPHA(2,I)+2.0*(THETA-THETA1)
      $=V1OV*SIN(BETA(2,I))
      BETA(1,I)=ARSIN($)+THETA1
      $=VOV*SIN(BETA(1,I))
      BETA1=ARSIN($)
      ALPH1D=ALPHA1*57.29578
      IALP1=ALPH1D
      I$=IALP1+31
      $=ALPH1D-IALP1
      INDEX=I$
      IF (ALPHA1.LT.0.0) INDEX=INDEX-1
      IF (INDEX.GT.60.OR.INDEX.LT.1) STOP 22
      XP=UPFUN(I$)+$*(UPFUN(INDEX+1)-UPFUN(INDEX))
```

```
      D1=VT21+XP*STH1
      D1=D1/COS(ALPHA(1,I)+THETA1)
C****
C     D1 IS LENGTH OF RAY PATH IN LAYER 1
C****
      XP=XP+D1*SIN(ALPHA(1,I))
      I2=IALP+1+ITHETA-ITHET1
      INDEXS=I2
      IF (ALPHA(2,I).LT.0.0) INDEXS=I2-1
      IF (INDEXS.GT.30.OR.INDEXS.LT.1) STOP 23
      AITDIV=FUNAD(I1,INDEXS+1)-FUNAD(I1,INDEXS)
      FUNAD1=FUNAD(I1,I2)+DELTA*AITDIV
      PATHNI=VT2+XP*STHM1/CTH1
      TIMENI=PATHNI/V
      XP=XP+FUNAD1*PATHNI*CTH1
      $=VT21/CTH1+XP*STH1/CTH1
      D1=D1+$/COS(BETA(1,I))
      XP=XP+$*TAN(BETA(1,I))
      BETA1D=57.29578*BETA1
      IBETA1=BETA1D
      I$=IBETA1+31
      $=BETA1D-IBETA1
      INDEX=I$
      IF (BETA1.LT.0.0) INDEX=INDEX-1
      IF (INDEX.GT.60.OR.INDEX.LT.1) STOP 24
      XP=XP+UPFUN(I$)+$*(UPFUN(INDEX+1)-UPFUN(INDEX))
      $=XP-X(I)
      IF (ABS($).LT.0.025) GO TO 155
C****
C     CALCULATE A NEXT APPROXIMATION TO ALPHA(2,I)
C****
      ALPHA(2,I)=ALPHA(2,I)-$/XP*FUNAD1/AITDIV/57.29578
      IALP=ALPHA(2,I)*57.29578
  150 DELTA=ALPHA(2,I)*57.29578-IALP
      STOP 25
C****
C     CALCULATE TCOR(I)=TIME CORRECTION ON I'TH TRACE AND
C     ALSO CALCULATE A FIRST APPROSIMATION TO ALPHA(2,I) FOR
C     NEXT I VALUE
C****
  155 TCOR(I)=TIMENI*(FUNAED(I1,I2)+DELTA*(FUNAED(I1,INDEXS
     .+1)-FUNAED(I1,INDEXS)))
      TCOR(I)=TCOR(I)+D1/V1+UPFUNT(IBETA1+31)+UPFUNT(IALP1+3
     .1)
      IF (I.EQ.NUMTR) GO TO 200
      ALPHA(2,I+1)=ALPHA(2,I)+(X(I+1)-X(I))/X(I)*FUNAD1/AITD
     .IV*APFACT/57.29578
      IALP=ALPHA(2,I+1)*57.29578
      DELTA=ALPHA(2,I+1)*57.29578-IALP
  160 CONTINUE
      STOP 26
  200 DO 210 I=1,NGATE
      SUM(I)=0.0
  210 SUMNOR(I)=0.0
```

```
C****
C    CALCULATE ISPEC AS A MEASURE OF GOODNESS OF FIT OF
C    REFLECTION ARRIVALS TO A PARTICULAR STEPOUT
C    SPECIFIED BY V, THETA, AND TO
C****
      DO 250 I=1,NUMTR
      INDEX=178.5714*(TCOR(I)-TIMINC)-IP+2.5
      DO 240 J=1,NGATE
      IF (INDEX.LT.1.OR.INDEX.GT.500) STOP 5
      SUM(J)=SUM(J)+A(INDEX,I)
      SUMNOR(J)=SUMNOR(J)+ABS(A(INDEX,I))
  240 INDEX=INDEX+1
  250 CONTINUE
      SUMSQ=0.0
      SUMNSQ=0.0
      DO 260 I=1,NGATE
      SUMSQ=SUMSQ+SUM(I)*SUM(I)
  260 SUMNSQ=SUMNSQ+SUMNOR(I)*SUMNOR(I)
      ISPEC(ICT3)=0
      IF (SUMNSQ.NE.0.0) ISPEC(ICT3)=SUMSQ/SUMNSQ*1000.
      V=V+VELINC
C
C****WRITE TIME CORRECTIONS ON DISK FOR GOOD CORRELATIONS.
C
      IF (ISPEC(ICT3).GT.800) WRITE (3) ICT1,ICT2,ICT3,(TCOR
     .(I),I=1,NUMTR)
  300 CONTINUE
      WRITE (6,7) TO,(ISPEC(I),I=1,NVEL)
      TO=TO+TIMINC
  400 CONTINUE
      ITHETA=ITHETA+ITHINC
  500 CONTINUE
    1 FORMAT (20A4)
    2 FORMAT (3I5,2F5.2,I5)
    3 FORMAT (12F5.3)
    4 FORMAT (2F5.3,I5,2F5.2,4I5)
    5 FORMAT ('1',20A4,' AT A DIP OF ',I3)
    6 FORMAT ('-TIME  VEL=',20(F4.2,2X))
    7 FORMAT (' ',F5.2,5X,20(I4,2X))
    8 FORMAT ('1X DISTANCES IN KM. FOR ',20A4,' FOLLOW:',//'
     . ',12F10.3)
    9 FORMAT ('-LAYER NUMBER = ',I1)
   10 FORMAT('0V1 = ',F5.3,5X,'T1 = ',F4.2,5X,'THETA1 = ',I3
     .)
  999 STOP
      END
```

```
      SUBROUTINE RGET(LUNIT,IN,A,N,ICODE,IP,IC,*)
C
C    THIS SUBROUTINE READS THE DATA OFF TAPE WITH THE AID OF
C    THE SYSTEM SUBROUTINE READ.  THE DATA WAS WRITTEN ON
C    THE TAPE AS VS TYPE RECORDS WITH BLOCKSIZE OF 2*IN-8.
C    THE BLOCKSIZE OF THE TAPE MUST BE < OR = 8200.
C    N IS THE NUMBER OF DATA POINTS DESIRED STARTING AT
C    POINT IP IN IA. IC IS THE CHANNEL NUMBER OF THE
C    CHANNEL THAT IS TO BE SKIPPED.  IF IC=0 NO CHANNEL IS
C    SKIPPED. ICODE IS THE NUMBER OF CHANNELS TO BE READ.
C
      INTEGER*2 INLEN
      REAL IA(4096)
      DIMENSION A(1)
      INLEN=IN
      IEND=ICODE
    1 FORMAT ('-BAD RETURN FROM READ IN GET')
      K=0
      IF (IC.NE.0) IEND=IEND+1
      DO 3 I=1,IEND
      CALL READ(IA,INLEN,0,LNR,LUNIT,&4)
      IF (I.EQ.IC) GO TO 3
      DO 2 J=1,N
    2 A(K+J)=IA(IP+J-1)
      K=K+N
    3 CONTINUE
      RETURN
    4 WRITE (6,1)
      RETURN 1
      END
```